The Feasibility of 3D Printing Technology as a New Construction Method for Houses in Saudi Arabia

By
Hashem Abdulrahman Alhumayani

Supervised by:
Prof. Wassim Jabi
Dr. Eshrar Latif

Thesis submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy
Welsh School of Architecture
Cardiff University

July 2022

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Acknowledgments

First and foremost, my appreciation and thanks go to Allah for his blessings in my life, me the strength, patience, and health to accomplish this thesis.

I would like to express my sincere gratitude and continuous thanks to my first supervisor, Professor. Wassim Jabi for his assistance, encouragement, valuable guidance, and insightful supervision through my PhD journey, which has led to the achievement of this thesis and its goals. At that time, Professor. Jabi was more than a supervisor for me; he was my most extraordinary colleague during my study period at Cardiff University.

My great thanks also go to my second supervisor, Dr. Eshrar Latif, for his support and thoughtful recommendations for developing my study. My grandmother, Fatima, may Allah have mercy upon her, provided me with love, advice, and motivation that made me who I am today. Even though she passed away before I finished my PhD, I still deeply believe my success today is a consequence of her sincere prayers.

Special thanks to my parents, Professor. Abdulrahman and Norah, for their prayers, love, and endless support throughout my whole life. I would also like to thank my brothers and sisters, Dr. Hesham, Faten, Faisal, Abdullah, Sarah, and Fatima, for their encouragement and support.

It gives me great pleasure to thank those who made this thesis possible, namely my wife Alanoud and my princesses, Deema, Reema, and Sarah. My heartfelt thanks to my devoted wife for her care, love, and support. It is an honour to have her in my life and to experience her unconditional love.

I would want to thank my PhD colleagues, staff members, and friends, who supported me during my journey. Finally, I am thankful to the Saudi government, represented by my employer Taibah University, which granted me this scholarship that allowed me to pursue my graduate studies in the United Kingdom.

Dedication

This work is humbly dedicated to

My dear Father Professor Abdulrahman & My Mother Norah

Whose support and encourage me to believe in myself and shower me with their prayers and love

My beloved Grandmother Fatima (may Allah rest her soul in Jannah)

For being my first mentor who encouraged me to believe in myself and who have always emphasized the importance of education

My Wonderful Wife Alanoud

For her support, love, and encouragement throughout our marriage

My Brothers (Dr. Hesham, Faisal, and Eng. Abdullah)

and **My Sisters** (Faten, Sarah, and Fatima)

For encouraging and supporting me throughout my life

My daughters Deema, Reema, and Sarah

Allah's highest blessing.

Abstract

3D printing technology is taking slow and small steps into the construction industry. Research has shown that several factors affect the adoption of this technology in the construction sector, such as cost, environmental performance, and structural performance. The housing sector in Saudi Arabia faces many challenges, such as the construction cost, the environmental impact on houses, the high demand for houses, etc. Moreover, within Saudi Arabia Vision 2030, the Saudi government has introduced initiatives such as sustainable building initiative and building technology stimulus initiative (BTSI). These initiatives will help improve the current challenges in the housing sector. However, there is a lack of studies regarding the environmental, economic, and social perception of 3D printing technology in large-scale buildings worldwide in general and specifically in Saudi Arabia. Therefore, this research aims to investigate the potential of leveraging 3D printing technology as a new construction method in Saudi Arabia. A comprehensive investigation is employed to compare 3D printing technology and conventional construction methods. It includes environmental, economic, and social aspects, taking into account achieving the highest level of sustainability in the housing sector.

To achieve the aim and objectives of this research, first, Life Cycle Assessment (LCA) is utilised to evaluate and compare the environmental performance of conventional and 3D printing technology construction methods. Second, cost analysis is performed to assess the economic aspect of both construction methods. Third, to examine the social aspect, Diffusion Innovations Theory (DIT) is used to investigate the adoption of 3D printing technology among professionals (Architects and Civil Engineers) in the construction sector in Saudi Arabia using an online survey.

The analysis demonstrated that 3D printing technology construction methods had a better environmental and economic impact than conventional construction methods. The online survey analysis revealed that all attributes of DIT (Relative Advantage, Compatibility, Complexity, Observability, and Trialability) supported the adoption of 3D printing technology among Saudi Arabian professionals. Additionally,

Trialability, Relative Advantage, and Observability had scored the highest attributes that professionals think will affect adoption. The overall findings of this research indicate that 3D printing technology would to be an excellent choice method to be adopted in the construction sector in Saudi Arabia from environmental, economic, and professional's aspects.

List of Publications

Alhumayani, H., Gomaa, M., Soebarto, V. and Jabi, W. 2020. Environmental Assessment of large-Scale 3D Printing in Construction: A Comparative Study between Cob and Concrete. *Journal of Cleaner Production* 270, p. 122463. Available at: https://doi.org/10.1016/j.jclepro.2020.122463.

List of Abbreviations

3DP	3D Printing
3DCP	3D Concrete Printing
AM	Additive Manufacturing
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
GaStat	General Authority for Statistics
SBCNC	Saudi Building Code National Committee
SBC	Saudi Building Code
REDF	Real Estate Development Fund
MOMRA	Saudi Ministry of Municipal and Rural Affairs
GHG	Greenhouse Gas
SAR	Saudi Riyal
BTSI	Building Technology Stimulus Initiative
RP	Rapid Prototyping
RM	Rapid Manufacturing
RT	Rapid Tooling
CC	Contour Crafting
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
SLA	Stereolithography
SLS	Selective Laser Sintering
LOM	Laminated Object Manufacturing
FDM	Fused Deposition Modelling
SGC	Solid Ground Curing
EBM	Electron Beam Melting
LENS	Laser Engineered Net Shaping
UAM	Ultrasound Additive Manufacturing
CC	Contour Crafting
TPB	Theory of Planned Behaviour
TAM	Technology Acceptance Model
UTAUT	Unified Theory of Acceptance and Use of Technology
DOI	Diffusion of Innovations Theory
DIT	Diffusion of Innovations Theory
SD	Sustainable Development
SC	Sustainable Construction
TBL	Triple Bottom Line
UNCED	UN Conference on Environment and Development
SDG	United Nations adopted the Sustainable Development Goals
SC	Sustainable Construction
USGBC	U.S. Green Building Council
SBTool	Sustainable Building Challenge Framework
BREEAM	Building Research Establishment Environmental Assessment Method
LEED	Leadership in Energy and Environmental Design

BQ	Bill of Quantity
EDP	Environmental Product Declaration
GCC	Gulf Cooperation Council
CFRP	Carbon Fibre Reinforced Polymer
GWP	Global Warming Potential
AP	Acidification Potential
EP	Eutrophication Potential
FFP	Fossil Fuel Depletion
POFP	Photochemical Oxidant Formation Potential
ODP	Ozone Depletion Potential
RADV	Relative Advantage
COMX	Complexity
COMP	Compatibility
TRB	Trialability
OBS	Observability

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Chapter 1: Introduction to Research

1.1. Introduction

This part of the study describes the research background, aim, objectives, questions, and an overview of the methodology of this study. Also, it presents the thesis structure and a summary of the chapter.

1.2. Research Background

From the dawn of the Industrial Revolution, our way of life has been deeply affected by technology. Technology has both developed and facilitated our lifestyles in many effective ways, such as in our health care system, education, construction industry and social life. (Saba 2009; Koskela and Kazi 2003; Atkinson et al. 2008; Buntin et al. 2011). By the end of the eighteenth century, the first Industrial Revolution started and introduced mechanical manufacture through the steam engine (Hudson 1992). Then, the second Industrial Revolution was launched at the start of the twentieth century. Within this revolution, electricity was used mainly by the labour force and in the mass-production sector (Hilton 2005). The following third Industrial Revolution started in the 1970s and introduced information technology (IT) systems and electronics, and further automated production (Xu et al. 2018). At the 2011 Hanover Fair, the German government presented the notion of the 4th Industrial Revolution, which was known as Industry 4.0 (Li et al. 2017).

The fourth Industrial Revolution represents cyber-physical systems that refer to digital, physical and biological sectors. The digital sector includes cloud computing, digital platforms, The Internet of Things (IoT), Artificial Intelligence (AI) etc.; the physical sector involves 3D printing (3DP), autonomous cars etc.; and the biological sector contains neurotechnology, genetic engineering etc. (Menges 2015; Li et al. 2017). The fourth Industrial Revolution can not only be used in product manufacturing but can also be applied in technology, business, consumption and any part of humans' daily life (Theorin et al. 2017; Ivanov et al. 2016; Sackey and Bester 2016). Additive Manufacturing (AM)—which is also identified as 3D printing (3DP)—is the procedure of creating three-dimensional objects by adding materials layer by layer, in contrast to what is known as subtractive manufacturing (ASTM INTERNATIONAL 2013). Furthermore, the 3D printing technology was originally presented late in the 1980s by Charles Hull (Ngo et al. 2018). Since then, the interest in adopting this technology grew in different areas such as aerospace, the architectural industry, automobile industry, medical industry etc. (Paul et al. 2018; Oropallo and Piegl 2016; Ramya et al. 2016). In the previous few decades, the building industry had experienced rapid change, transforming new technology, innovative processes and cutting-edge materials (Yin et al. 2018). Construction companies nowadays are facing several significant obstacles in terms of construction cost, high impact on the environment, low labour productivity on construction sites, material waste and the time of construction (Hwang et al. 2015; Sun et al. 2018; Maskuriy et al. 2019). Nowadays, 3D printing technology is adopted in the construction industry, but this technology is still in the development and research phase (Wang et al. 2014; Craveiro et al. 2019; Soliman et al. 2015; Hossain et al., 2020).

Sustainability is known as the process of meeting the present requirements without risking the needs of future generations (Brundtland Commission 1990). Sustainability has three dimensions, including economy, environment, and society (Elkington 1998). Sustainability aims to preserve the natural and constructed ecosystems for next generations while also assuring the survival of natural resources and human beings (Yılmaz and Bakış 2015). The International Energy Agency reported that since 2010, the average growth rate of the world's energy consumption has almost doubled (International Energy Agency 2018). Furthermore, in 2018 alone, CO_2 emissions increased by 1.7% due to the high energy demand; this increase was recorded as a new historical record (International Energy Agency 2018). In 2018, the building construction industry and its operations accounted for 36% of worldwide overall energy consumption and 40% of CO_2 emissions (IEA and UNEP 2018). At the same time, Shrubsole et al. (2019) declare that buildings play a vital part in transferring to a low-carbon economy.

Philipp et al. (2016) state that the construction sector is considered a keystone for the world economy. In 2016, the construction sector accounted for nearly $10 trillion in annual sales, which is around 6% of the global GDP. In 2018, the construction investment was $11.4 trillion and in 2025, the prediction is that the construction sector will rise to $14 trillion (Statista 2020). Moreover, 8.4% of the global workforce comes from the construction sector (ILO 2020). For several years, the construction industry failed to increase efficiency because of the minimal usage of technology and the highly dependency on human labour force (García de Soto et al. 2018). There are multiple reasons that affect the cost of construction such as labour costs, equipment expenses and material usage (Weng et al. 2020).

In both developed and developing countries, housing availability is widely acknowledged to be one of society's highest concerns (Alqahtany 2019). Since oil discovery, Saudi Arabia is considered among the world's fastest-developing countries, with an annual economic growth rate of 6.8% (Al-Tamimi 2017). This remarkable growth has resulted in fast expansion, urbanisation and growth in all sectors, including the building industry, allowing for the fulfilment of the standard of living in a population that is rising at the same rate as the demand. Considering the increase in the building sector, data shows that just 30% of Saudi people own their homes, compared to an average of 70% globally (Mulliner and Algrnas 2018). Although there is an increase in the growth rate of buildings in Saudi Araba, there is more than one factor that affects the development of the construction sector such as population growth and high demand for housing, land and housing in Saudi Arabia, current construction methods issues and the lack of involving recent methods, environmental challenges, and high cost of construction, which are discussed thoroughly in Chapter 2. With the house's crisis and the need for environmental, economic, and social sustainability, many governments, such as that of Saudi Arabia, had made serious plans to obtain these issues. On 25th April 2016, under the supervision of King Salman Bin Abdelaziz, the Saudi Council of Ministers approved "Saudi vision 2030" (Alqahtany 2020). This vision was constructed under three themes: an ambitious nation, a thriving economy, and a vibrant society (Saudi Vision 2030 2020). The vision is going to build a vibrant society where all residents can achieve their visions of living within a well-established economy. There are 13 programs inside the vision, such as quality of life, housing program and fiscal balance program (Saudi Vision 2030, 2020). Moreover, the housing program seeks to propose solutions for the citizens to own houses according to their finance and needs

(Housing Program 2020). Within the program, there is more than one initiative. Adopting and investing in advanced building technology (4.0) is one of the initiatives that concentrates on adopting the latest technologies in construction, such as 3D printing technology (Housing Program 2020). By 2030, the Saudi government is willing to have 1.5 million 3D printed houses across the country (Ministry of Housing 2018). Another program is the quality of life program which seeks to improve the lifestyle of individuals (Quality of Life Program 2020). This program has a lot of targets, one of them is "clean air," which aims to reduce CO_2 emissions (Quality of Life Program 2020).

This PhD research intends to assess the adoption of 3D printing technology as a new construction method in Saudi Arabia from an environmental, economic, and professional aspect. This is done by filling the gaps in the existing literature knowledge as discussed in Chapter 2. Furthermore, this research tries to present the innovative aspect of 3D printing technology. Finally, the outcomes of this study may then be generalised to other countries that have similar characteristics to Saudi Arabia, such as the Gulf Cooperation Council (GCC) countries and several other Middle Eastern countries.

1.3. Research Aim, Objectives, and Questions

This study aims to investigate the potential of leveraging 3D printing technology as a new construction method in Saudi Arabia in achieving a higher level of sustainability. This investigation will be based on a comparison between 3D printed technology and conventional construction methods including environmental, economic and social aspects.

To achieve this aim, the questions of this research are presented as follows:

1- What is the difference in the environmental impact between 3D printed technology and conventional houses in Saudi Arabia?
2- What is the difference in the economic impact between 3D printed technology and conventional houses in Saudi Arabia?

3- Will 3D printing technology be accepted as a new construction method among the professional community in Saudi Arabia?

The objectives of this research include the following:

- Survey the literature to assess the current construction methods used in Saudi Arabia.
- Survey the literature to investigate the 3D printing technology construction methods on large-scale buildings.
- Survey the literature to explore the theories of adopting new technologies.
- Survey the literature to assess the importance of sustainability along with the existing environmental performance methods for buildings.
- Use LCA methods to evaluate the environmental impact of conventional and 3D printing technology methods.
- Perform a cost analysis to assess the economic aspect of conventional and 3D printing technology methods.
- Conduct a questionnaire to investigate the professional's attitude and willingness towards adopting 3D printing technology construction methods as a new construction method in Saudi Arabia.

1.4. Methodology

To accomplish the research objectives, this research was divided to five parts. These parts are an extensive literature review, research design and methodology, a comparison study (LCA) of conventional and 3D printing construction methods for a domestic villa in Al Khobar, Saudi Arabia, a cost analysis study of conventional and 3D printing technology construction methods and an analytic study of the construction industry's perception of the 3D printing technology construction method.

1.4.1. Part 1: Literature Review

The literature review part is divided into three main sections: an overview of Saudi Arabia, 3D printing technology and sustainability development. The first section's purpose is to explore the housing sector in Saudi Arabia and assess the current issues and challenges in the housing sector. The second part aims to discover 3D printing technology in general and specifically in large-scale building constructions. Furthermore, this part evaluated the different theories of adopting new technologies and presented different studies that were conducted to assess the adoption of 3D printing around the world. The last part concentrated on understanding sustainability, in general, and specifically the impact of construction on the environment. Moreover, this part overviewed buildings sustainable rating tools and narrowed its focus on presenting the conducted Life Cycle Assessment (LCA) studies in Saudi Arabia and 3D printing technology. Finally, after the comprehensive assessment of the literature review, the literature reviled that there is a gap that needs to be fulfilled.

1.4.2. Part 2: Research Design and Methodology

In this part, different philosophical paradigms were assessed, and the positivism philosophical approach was chosen as it aims to achieve the research objectives and answer the research questions. After reviewing the different types of research approaches, this study chose a deductive approach, which agrees with the research questions, aim and objectives. Moreover, this research adopted the quantitative method as this method offers specificity and intense detail to the research outcomes (Denzin and Lincoln 2005; Myers 2009).

1.4.3. Part 3: A Comparison Study (LCA) of Conventional and 3D Printing Technology Construction Methods for a Domestic Villa in Al Khobar, Saudi Arabia

This part begins with introducing Life Cycle Assessment (LCA) as a tool for environmental assessment and the justification for choosing this method. This introduction contains an overview of the LCA framework's goal and scope, life cycle inventory, the Life Cycle Assessment method and the interpretation of the results. Furthermore, the LCA study will be conducted on a one-story domestic villa in Al Khobar City in Saudi Arabia using four scenarios of construction methods, two conventional construction methods and two 3D printing technology construction methods. All the processed of data collection and analysis for the four scenarios are presented in depth in Chapter 3.

1.4.4. Part 4: Cost Analysis Study of Conventional and 3D Printing Technology Construction Methods

This part presents the economic assessment (cost analysis) of the 3D printing technology construction methods compared to conventional construction methods. The assessment will be done on the same four scenarios presented in part 3. Moreover, the cost analysis for this study will calculate the material and construction costs. The data collection will be presented in detail in Chapter 3.

1.4.5. Part 5: Analytic Study of Construction Industry Perception of 3D Printing Technology Construction Method

This part starts by describing the development of the questionnaire to measure the professional's attitude and willingness towards adopting 3D printing technology construction methods as a new construction method in Saudi Arabia. It also presents the Diffusion of Innovations Theory and describes the theory factors, procedures, attributes, limitations and justifications for choosing this theory. Additionally, this part will introduce the questionnaire design, which covers the development of the questions and the scale of ranking, for this study. After that, the development of the hypothesis for each attribute will be presented. This part will present the process of the questionnaire translation, pilot study, validity and reliability, questionnaire sampling size, ethical consideration, data collection technique and data analysis. All the processes can be found in Chapter 3.

1.5. Thesis Structure

- Chapter One: *Introduction*

This chapter offers an overview of the research background and the issues related to the topic. This chapter also presents the research aim, objectives, research questions and the methodology of the conducted study. Moreover, it presents the thesis structure and a summary of the chapter.

- Chapter Two: *Literature Review*

The literature review chapter is divided into three parts. The first part seeks to provide an overview of the case of this research location in Saudi Arabia through a relevant literature review. This part presents a clear understanding of the Saudi Arabian housing system. Furthermore, it offers different types of contemporary houses in Saudi Arabia with the usage of different construction methods and materials. This part also discusses the issues that are faced by the housing industry in Saudi Arabia and the efforts and initiatives that the Saudi government is willing to apply to solve these challenges. The second part of the literature discusses the 3D printing technology construction method for large-scale buildings. This part offers an understanding of this technology and its different types. Furthermore, this part presents the different materials used in this technology and also the economical aspect of it. An example of 3D printed construction buildings from around the world is presented to have a better understanding of how the field is working. Finally, this part presents different theories for adopting new technology. This section also delivers the different theories used to study the adoption of 3D printing technology in previous studies in the literature. The last part of the literature review chapter discusses sustainability and sustainability development. Also, this part presents the efforts made by the United Nations (UN) to apply sustainability in different areas. This part also produces sustainability in construction and discusses the effect of construction on the environment. It presents the different methods and tools for environmental assessment and also the chosen method for this study, which is LCA. Finally, it introduces the use of LCA in Saudi Arabia and 3D printing from previous literature.

- Chapter Three: *Research Design and Methodology*

This chapter offers the design and the adopted methodology for this study. It delivers the three parts of the work: an environmental assessment (LCA) of conventional and 3D printing construction methods for a domestic villa in Al Khobar, Saudi Arabia; an economic analysis study of conventional and 3D printing construction methods for the same villa; and an analytic study of a professional's perception of the 3D printing construction method in Saudi Arabia. Furthermore, the data collection and analysis process are presented in each part separately. Finally, this chapter also describes the methodology framework and concludes with a brief summary of the chapter.

- **Chapter Four:** ***The Environmental and Economic Results and Analysis of 3D Printing Technology vs Conventional Construction Methods***

This chapter provides the result analysis of the environmental aspect (LCA) and the economic aspect of the comparison of conventional and 3D printing technology construction methods.

- **Chapter Five:** ***Results and Analysis of Professional's Attitude and Willingness Towards the Adoption of 3D Printing Technology in the Construction Industry***

This chapter presents the results and analysis of the questionnaire survey that will be performed to assess the adoption of 3D printing technology in the construction industry in Saudi Arabia.

- **Chapter Six:** ***Discussion***

This chapter discusses and compares the findings from Chapters 4 and 5 with the existing literature to identify the similarities and differences between them. After that, the findings of the discussion will be mapped with Saudi Arabia's housing industry. Finally, the key research findings and the chapter summary will be presented.

- **Chapter Seven:** ***Conclusion***

This chapter summarises the achievement of the research objectives, research limitations, contributions to the body of knowledge and recommendations.

1.6. Chapter Summary

This chapter has presented the research background of this study. It presented the research aim, objectives, questions, and the methodology of this study. Moreover, this chapter offered the thesis structure and a summary of the chapter. The next chapter will represent and discuss the literature review of this study.

Chapter 2: Literature Review

2.1. Introduction

This chapter describes the literature review conducted in the research study. This chapter aims to demonstrate a thorough evaluation of the relevant literature, identify the research gap, and define the research questions. This chapter is constructed as follows: the first section introduces a detailed assessment of the case of Saudi Arabia and its building sector. A brief history of the country is provided, including its location, provinces, population, and climate. Next, The Saudi housing sector is examined in depth in this section. This assessment was made by reviewing the Saudi contemporary housing development, types of houses in Saudi Arabia, methods and materials used in the construction industry in Saudi Arabia, Saudi building code, houses challenges in Saudi Arabia and Saudi Arabia's vision 2030. The second section offers a review of the 3D printing technology. It starts with introducing the technology, its history, and its principles. The section also provides the different technologies and materials used in 3D printing, concentrating on the construction sector, the economic aspect of the 3D printing technology in construction, the pros and cons of the 3D printing technology and innovation theories used to study the adoption of the 3D printing technology. The third sections provide an understanding of sustainability and sustainability development, in general, and in construction, particularly. This section also introduces and reviews the impacts of construction on the environment, methods and tools offered for environmental performance for buildings and the Life Cycle Assessment method will be discussed in both Saudi Arabia and 3D printing technology. Finally, the chapter will identify the research gap and future direction.

2.2. Overview of Saudi Arabia and its Housing Sector

2.2.1. Location and Profile of Saudi Arabia

Saudi Arabia is located in western Asia's southernmost region. It occupies approximately four-fifths of the Arabian Peninsula, with a total area of around 2,149,690 km2, somewhat more than one-fifth of the United States of America (CIA, 2021). The country is bounded on the east by the Arabian Gulf, Qatar, and UAE; the west by the Red Sea; on the north by Jordan, Iraq, and Kuwait; and on the south by

Oman and Yemen. Additionally, Abdul Aziz Ibn Saud formed Saudi Arabia in 1932 (UKSACB, 2021), and the nation is divided into 13 distinct administrative areas or provinces (UKSACB, 2021) as can be found in (Figure 2:1).

Figure 2-1 Map of Saudi Arabia.

Saudi Arabia contains multiple cities, each with its climate, culture, trade, soil, vegetation, and infrastructure. Moreover, Saudi Arabia's capital is Riyadh, the country's largest metropolis. Among the other significant cities is Jeddah, the country's second-biggest city and the primary seaport on the Red Sea. Makkah and Madinah are Islam's two holiest cities for pilgrimage and devotion (Shukri et al. 1996). Apart from Makkah and Madinah, Saudi Arabia has several other significant cities, including Najran, Abha, Dammam and Hail. In mid-2020, the overall population was predicted to be 35,013,414 individuals (GaStat 2021). According to the July 2017 demographic characteristics survey, the population growth is 2.52% (GaStat, 2021). Arabic is the most frequently spoken language, while Islam is the predominant religion. Saudi Arabia's population is believed to be predominantly youthful. In 2020, the General Authority for Statistics (GaStat) produced a special report named "Saudi Youth Report in Numbers" in commemoration of World Youth Day (SADSC 2020). The percentage of children and youth of the age group (0–34) in the Saudi population in 2020 represented 67%.

2.2.2. Climate of Saudi Arabia

Saudi Arabia's climate may be defined as an arid desert, with severe temperature changes in the interior. Similarly, coastal locations have high humidity and temperatures (Majed Sultan Abu Ashwan et al. 2012). According to the Koppen-Geiger classification, Saudi Arabia's climate is classified as a dry desert (Figure2-2).

The summer temperatures in Saudi Arabia may reach 43°C, which makes it one of the few countries that reaches this degree (CCKP 2021). Additionally, temperatures are pretty high between April and November, making it tough for individuals to manage without air-conditioning. Due to the different topographical areas in Saudi Arabia, the climate is different from one region to another. Alrashed and Asif (2015) categorised Saudi Arabia's climate zones into six separate climate zones.

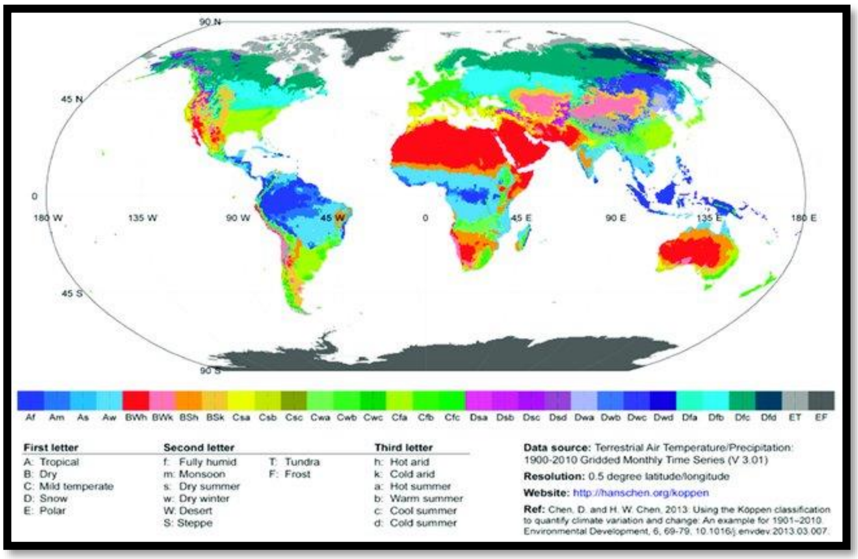

Figure 2-2 World Map of the Koppen-Geiger Climate Classification System.

Given that the Empty Quarter is an empty region, five areas have been defined as representations of the five habitable climatic zones. Riyadh, a desert subzone with a dry and hot climate; Jeddah, a maritime subzone with dry and hot climate; Khamis Mushait, a subtropical area with a mountainous subtype and Mediterranean subzone; Dhahran, a marine subzone with a dry and hot climate; and Guriat; a desert subzone with cold and dry. Regarding rainfall, the Asir Mountains in the southern portions have a high annual average rainfall and mild temperatures. Meanwhile, the annual average rainfall in the rest parts Saudi Arabia is exceedingly unpredictable and low. The temperature is high, and the humidity is low, except for minor parts of the coastal regions (Al-Ahmadi and Al-Ahmadi 2013).

2.3. Housing in Saudi Arabia

2.3.1. Development of Contemporary Housing in Saudi Arabia

According to Aba Alkhail (1989), Saudi’s economic development may be divided into four stages throughout history. The first stage occurred prior to the oil discovery in the 1930s. The second stage began shortly after the discovery of oil and continued for more than three decades. The third stage was the economic boom era (the 1970s and early 1980s), and the fourth period began following the economic boom and continues to the present. A literature review was undertaken to determine what variables aided Saudi Arabia's transition to modern architecture.

The Arab American Oil Company (ARAMCO) was the first to adopt the concept of street planning and construction utilising cement and reinforced concrete instead of mud bricks or stone and wood roofing, as in traditional construction, in 1947. Aramco was tasked with planning Al Khobar and the future expansion of Dammam in the eastern region in order to rein in growth surrounding the oil fields. This resulted in Saudi Arabia’s first planned settlements (figure 2:3 and figure 2:4) (Al-Naim 2008).

According to King (1998), a quick and particularly intensive rate of architectural change has reached every section of Saudi Arabia as a result of an increase in oil costs related to the oil crisis of the 1970s. Saudi Arabia has also become a popular business location for companies from all over the world. Many international architects, engineers and construction professionals were brought to Saudi Arabia to help establish a contemporary built environment. This included imported models and the modernising movement that swept across most of the country's cities after discovering oil in 1950.

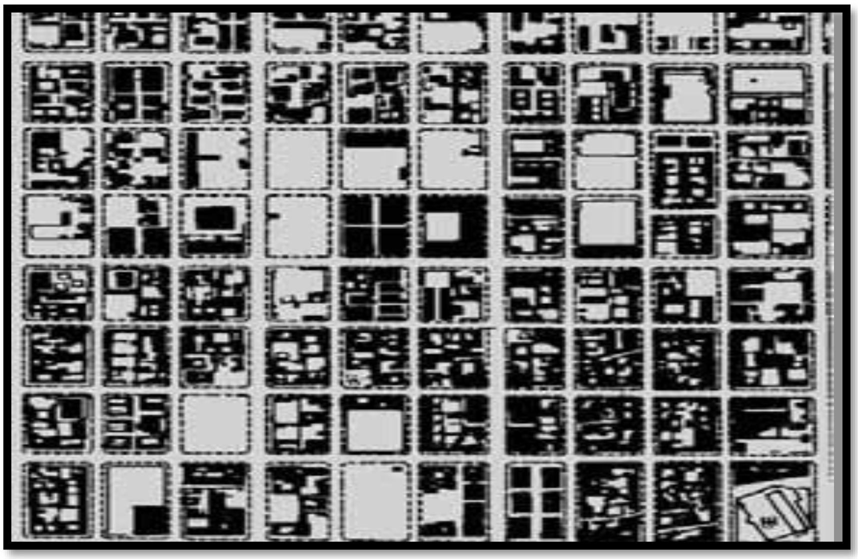

Figure 2-3 Planning System of Al Khobar.

Figure 2-4 Villa type in Dammam (1950s).

There have been many historic buildings, such as mosques, demolished during this phase of modernisation (Elsheshtawy 2008). According to Saleh (1998), Saudi Arabia's traditional cities, towns and villages have begun to lose their architectural identities and represent foreign forms (Figure 2-5) (Al-Naim 2008). Shihabi (2004) observed that most traditional residences are being demolished to make room for contemporary ones. He also stated that Saudi had experienced significant changes in terms of lifestyle, which are impacted by various external and internal factors.

As a result, the architectural heritage in Saudi Arabia suffered greatly throughout the 1970s and 1980s. Furthermore, the increase in land costs in cities caused the demolition of old houses (Kultermann 1999). Alafghani (1991) points out that the Saudi government stated the objective of a “house for every person” during the economic boom. As a result, the Ministry of Municipalities and Rural Affairs began offering financial support, interest-free loans and land grants to help individuals build their own homes. All the factors mentioned above resulted in the development of different types of contemporary homes, that will be explained in the next section.

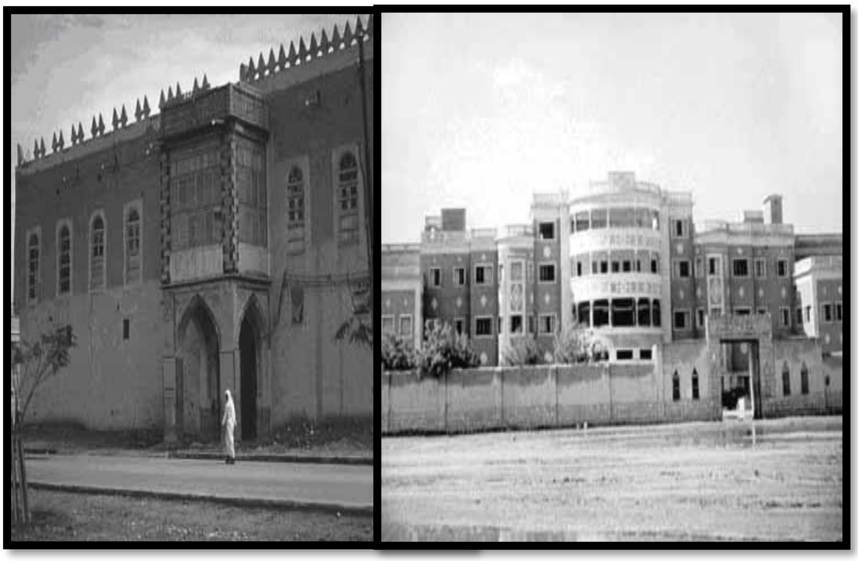

Figure 2-5 The Change of Architectural Identity (Al-Naim 2008).

2.3.2. Types of Contemporary Houses in Saudi Arabia

The General Authority for Statistics in Saudi Arabia (GaStat 2019), states that there are five types of housing in the country. These are apartments, a floor in a traditional house, a floor in a villa, villas, and traditional houses. (Table 2-1) describes the distribution of the five dwelling typologies across Saudi Arabia's 13 administrative areas.

Table 2-1 The Types and Numbers of Housing Units in Saudi Arabia's 13 Administrative Areas (GaStat, 2019).

Administrative Area	Apartment	A Floor in a Traditional House	A Floor in a Villa	Villa	Traditional House	Total
Al-Riyadh	288360	1638	131672	395560	48160	865390
Makkah Al-Mokarramah	576285	10150	21090	117827	183876	909228
Al-Madinah Al-Monawarah	151575	687	2604	37341	60840	253047
Al-Qaseem	15100	19	31992	97980	25857	170948
Eastern Region	253116	10582	30628	176118	57770	528214
Aseer	111972	1140	32512	112326	57312	315262
Tabouk	78174	282	1222	8379	38055	126112
Hail	14241	78	3564	34675	31825	84383
Northern Borders	10842	1939	4698	16500	6552	40531
Jazan	32560	378	11970	33864	103649	182421
Najran	28032	5	4100	18018	22411	72566
Al-Baha	29232	67	5248	24089	14056	72692
Al-Jouf	20919	238	2788	22560	14628	61133
Total	1610408	27203	284088	1095237	664991	3681927

- **Apartment**

Apartments are a form of accommodation for Saudi society's middle class, who are not able to afford building their own private homes (Taleb 2011). Apartments, which may be found in many Saudi cities, are designed to house many families in a smaller space (Taleb 2011). Apartments are made up of several rooms in a multi-story building (often a designated residential block) (Aldalbahi 2020). An apartment typically has a living room, a dining room, a kitchen, and two or three bedrooms. In Saudi Arabia, the rapid population growth necessitated the rapid improvement of inexpensive living spaces within the form of many apartments or flats in different apartment complexes or structures (Alshahrani and Boait 2019). They are frequently viewed as a way to get in the real estate market or as a necessity when no other choice is available (Ahariqi et al. 2008) (Figure 2-6).

Figure 2-6 An Example of an Apartment Complex Building (Design concept 2014).

- Traditional House

"The traditional housing is a simple house; also called Arab House" (Alzamil 2014a). The whole land area is utilised for construction (Alrashed and Asif 2014). This type of housing is common in old city centres, slums, small towns, and rural areas. The house is designed around a courtyard plan inspired by Islamic social and religious values that emphasises the importance of privacy for residents (Bahammam 1998). Low-income families often are the occupiers of traditional houses (Alshahrani and Boait 2019) (Figure 2-7).

Figure 2-7 An Example of a Traditional House (Maskny 2012).

- **Villa**

A *villa* is defined as a "semi-detached or detached suburban residence" (Collins Dictionary 2021). A villa is a modern style of dwelling that is popular in new metropolitan areas (Ahariqi et al. 2008). The villa is defined by a yard and a fence that protects the property's limits (Table 2011). Small villas, duplex villas and palaces are examples of this form of dwelling (Alzamil 2014). Moreover, villas became the most common style of residence in Saudi Arabia for average families, built and designed as detached, two-story houses for individuals based on their preferences (Bahammam 1998). Building materials and construction technological advancements made these new dwellings incredibly desirable, beginning a new age in cultural interests where traditional houses started to be undesirable, seen as old-fashioned and unsuitable for modern life (Aldalbahi 2020) (Figure 2-8).

Figure 2-8 Example of a Villa (Aldoshan 2021).

2.3.3. Construction Materials and Methods for Houses in Saudi Arabia

As previously stated, Saudi Arabia's movement to contemporary architecture has resulted in a greater dependence on imported modern technologies, designs and building materials. Houses in Saudi Arabia were historically built from wood, mud, brick and clay depending on which material was adaptable, accessible and suited to the environment and topography (Alrashed et al. 2017). Traditional building methods and materials in Saudi Arabia, without a doubt, could neither manage the difficulties of a modern city nor could they close the gap between contemporary and traditional architectural trends (Shihabi, 2004; Sidawi, 2013). In the 1950s, non-traditional construction technologies and building materials such as terrazzo tiles, concrete blocks, aluminium and glass were imported and used for the first time (Bahammam 1998; Saleh M. A. E. 1998; Mubarak 2004; Talib 1984). Since then, Saudi Arabia has used cement-based materials to help build new homes that meet the current criteria, such as many electrical fixtures and a large number of sanitary fittings (Mubarak 1999).

There are two conventional construction methods used for housing construction in Saudi Arabia, the conventional construction method (in-situ) and the precast construction method (off-site) (Alabbasi et al. 2021). The conventional method of construction (in-situ) refers to the completion of the building construction work at a proposed site (Mydin et al. 2014). It has onsite preparation of building components after the initial installation of reinforcing steel, wood formwork or plywood. (Badir et al. 2002). The precast construction method (off-site) is a stage-by-stage procedure that includes creating structural components in a factory-set environment (to the appropriate dimensions from the design), transporting these components to the site and erecting and assembling them on-site (Nanyam et al. 2017). In Saudi Arabia, the reinforced concrete frame (RC) is the most commonly adopted construction system (Bahammam 1998) (Table 2-2). This system offers considerable potential because of its durability, the ability to construct variable volumes, flexibility, and long spans (Almehrej 2015). Although both construction methods use a reinforced concrete frame, the technique of construction is different.

Table 2-2 The Types of Houses in Saudi Arabia's 13 Administrative Areas According to the Building Material (GaStat, 2019).

Administrative Area	Reinforced Concrete	Block/Brick	Stone	Total
Al-Riyadh	853910	11480	0	865390
Makkah Al-Mokarramah	783102	126126	0	909228
Al-Madinah Al-Monawarah	214515	38532	0	253047
Al-Qaseem	155569	15379	0	170948
Eastern Region	496944	31270	0	528214

Administrative Area	Reinforced Concrete	Block/Brick	Stone	Total
Aseer	277850	37412	0	315262
Tabouk	115362	10750	0	126112
Hail	62675	21708	0	84383
Northern Borders	40531	0	0	40531
Jazan	119436	62543	442	181979
Najran	60229	12337	0	72566
Al-Baha	67484	5208	0	72692
Al-Jouf	60098	1035	0	61133
Total	3307705	373780	442	3681485

The conventional method of construction (in-situ) consists of reinforced concrete columns and beams with concrete or clay blocks in the middle to construct external and interior walls (Bahammam 1998; Alyami et al. 2013). Columns and beams are prepared in-situ using plywood or wood formwork by labourers (Badir et al. 2002), where concrete or clay blocks are delivered from the factory. Moreover, there are two ways of delivering concrete; preparing the mix in-situ or delivering it as a ready mix from the factory (Ferraris 2001). The roof is made of a lightweight slab of either lightweight hollow clay blocks or concrete and insulated with insulation boards with a thickness of 10 to 15 cm (Almehrej 2015) (Figure 2-9).

Figure 2-9 Construction Process Using Traditional Construction Method.

The precast construction method (off-site) elements can include components such as beams, columns, staircases, bathrooms and in-filled walls that are prepared in a controlled environment (Nanyam et al. 2017). Different precast systems must be understood in order to comprehend the building of a precast concrete structure. Precast systems have been categorised into four basic systems based on the load-bearing structure: Slab-column system with a shear wall, Frame system, mixed or modular system, and large panel system (Brzev & Guevara-Perez 2010; Lakra et al. 2015). Furthermore, there are three types of walls in the precast methods: Cladding or Curtain walls, load-bearing walls and shear walls (NPCA 2014). The roof system in the precast construction method is called Hollow core Slab. Hollow core slabs are precast and prestressed concrete components produced on long line steel casting pallets. They are normally 1200mm broad (but can range from 600mm to 2400mm) and range in depth from 150mm to 500mm (IPHA 2021). Spans up to about 20m are possible, and applications range from single-family homes to residential flats, hospitals, office buildings, parking garages, hotels, supermarkets and schools (IPHA 2021) (Figure 2-10). Previous studies such as (Suryakanta 2014; Reichenbach & Kromoser, 2021; Molavi & Barral, 2016) have identified the advantages of Precast construction method as follows:

- The setting for factory prefabrication can enhance product quality.
- When necessary, the precast constructions may be removed and reused in another location.
- When compared to the conventional method, the work in the precast method may be accomplished in a shorter period of time.
- When installing precast buildings, it is obvious that the number of scaffolding and formwork is significantly decreased.
- It can result in a safer and cleaner construction.
- The ability of producing larger unobstructed span.
- The reuse of formwork in factory for multiple times compared with conventional methods.

Figure 2-10 Preparing Prefabricated Construction Buildings.

2.3.4. Saudi Building Code

The establishment of the SBC (Saudi Building Code) was one of the priorities of Saudi Arabia's government (Alaidroos & Krarti, 2015; Krarti et al., 2017). SBC is considered as a set of administrative, technical, and legal requirements and regulations that determine the minimum building construction standards to maintain public health and safety (SBC 2007). On 11th June 2000, a Royal Decree ordered the establishment of a national committee constituting representatives of private and governmental and Saudi universities (SBC 2007). In September 2001, the Council of Ministers authorised the National Committee's board plan for preparing a national building code for Saudi Arabia (SBC 2007). A variety of codes have been reviewed to select a basis code for the Saudi Building Code. The National Committee has been briefed on the findings of the national study as well as the international codes from Australia, Canada, the U.S.A, Arab and European codes (SBC 2007). The Saudi Building Code National Committee (SBCNC) was given permission to involve all or any pieces of material from the ICC codes (SBC 2007). In 2007, the public could access the first edition of the SBC, as well as requirements from many sectors such as architectural, structural, energy conservation, fire prevention, mechanical and electrical (SBC 2007).

2.3.5. Housing Challenges in Saudi Arabia

Housing availability is recognised as one of the most pressing issues affecting developed and developing countries (Alqahtany 2019). Several difficulties in the housing industry have evolved in Saudi Arabia over the last two decades, and it has become essential to address them appropriately (Alqahtany & Bin Mohanna, 2019). Though it is nearly difficult to address every area of concern, an effort has been done to emphasize those that are considered to be relevant. The main factors affecting the development of the construction sector in Saudi Arabia are:

- Population growth and high demand for housing
- Land and housing in Saudi Arabia
- Current construction methods' issues and the lack of using modern methods.
- High costs of construction
- Environmental challenges

2.3.5.1. Population Growth and High Demand for Housing

With a population of 35,013,414 million people, a land area of 2,149,690 km2, a population density of 16.2 people per km2 and a population growth rate of 1.7%, Saudi Arabia is considered to be one of the fastest growing countries in the world (GaStat 2021). From 1950 to 1980, the Saudi population grew from 5.8 million to 9.8 million. In 2015, the population was 34.7 million and in 2020, it became 34.7 million (GaStat 2021). Moreover, in 2025, 2030 and 2035, the population is expected to reach 37.2 million, 39.4 million and 41.3 million, respectively (Al-Alola et al. 2021). (Figure 2:11) .presents the population growth in Saudi Arabia. According to Bahammam (2018), the first housing crisis occurred towards the end of the 1960s due to the rapid population growth. During the 1970s "oil boom," Saudi Arabia's population grew at an incredible rate, adding significantly to the housing deficit as demand for homes and services outpaced the government supply (Garba 2004).

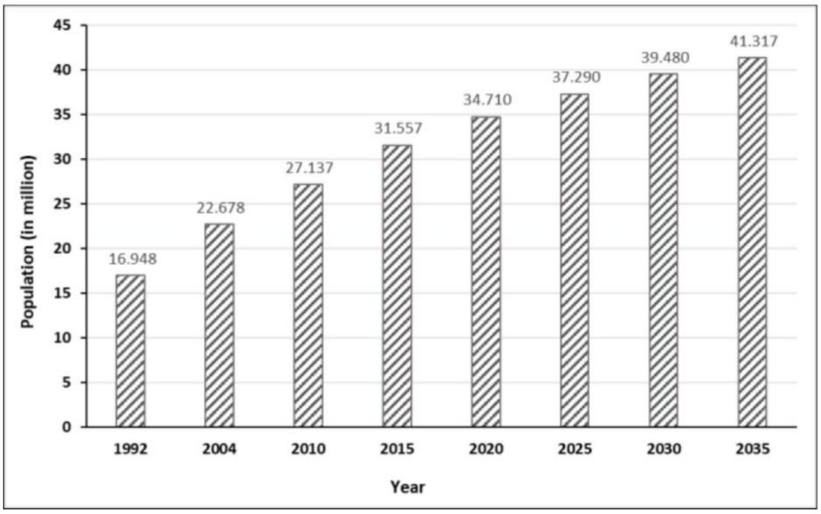

Figure 2-11 Saudi Arabia Population Growth Rate (Al-Alola et al. 2021).

The government formed the "Real Estate Development Fund" (REDF) in 1974 with the intention of offering residents interest-free housing mortgages. The amount for the given mortgage was ($130,000) as well as a payback period of 25-year to help residents build up their homes. In total, the REDF had a capital of $66 million when it was founded (Bahammam, 2018; Alqahtany, 2019). The REDFs' resources have been exhausted by the high demand for loans and the growing gap between the requests and the rate during which loans have been made in the last decade as a result of the population growth (Alqahtany 2019).

In Jeddah, for example, the number of buildings has grown massively in the previous fifty years due to population growth, from around half a million to more than four million (Felimban et al. 2019). According to an examination of the construction sector in Saudi Arabia delivered by the Saudi Ministry of Municipal and Rural Affairs (MOMRA), the number of issued building permits in Saudi Arabia has increased significantly over the previous two decades from 43,733 in 1995 to 164,102 in 2020 (MOMRA 2020). Therefore, the necessity for housing and the rapid rise in population has stressed the need for dwellings to be built as soon as possible (Ahmed et al., 2019; Mulliner & Algrnas, 2018). Estimates imply that with the expansion of the population, the country would need to build roughly 3 million additional residences by 2025 (SaudiGazette 2015).

2.3.5.2. Land and Housing in Saudi Arabia

Land availability is an essential part of Saudi Arabia's housing supply (Alzamil 2014). In Saudi Arabia, housing land is divided into developed and undeveloped lands (Alzamil 2014). To begin with, developed land is a land that has been planned and is suitable for building housing units. In this case, MOMRA provides services, infrastructure, and other facilities. Typically, the developed land is located inside municipal boundaries, and the landowners could be personal owners who want to build their own houses or landowners who want to sell lands. Second, undeveloped land is a land that has not been planned out and does not have any infrastructure. It is in the same area as cities.

Moreover, speculators purchase undeveloped land intending to sell it at a high price after the infrastructure is built (Sultan et al. 2012). (Table 2-3) shows 1,814,984 hectares of undeveloped land in Saudi Arabia, which equals 37% of land for housing. The data shown in Table 1 indicates that several regions have a considerably high percentage of undeveloped land: Medina (92%), Mecca (71%), Al Jouf (61%), Najran (55%), Qassim (55%) and Jazan (50%) (Alzamil 2014).

Table 2-3 Residential Land Areas in Saudi Arabia (Hectares) (Alzamil 2014).

Administrative Area	Developed land				Undeveloped land		Total (ha)
	Used (ha)	(%)	Vacant (ha)	(%)	Vacant (ha)	(%)	
Al-Riyadh	67,458	19	156,333	44	128,909	37	352,700
Makkah Al-Mokarramah	244,243	24	45,303	4.5	708,800	71	998,346
Al-Madinah Al-onawarah	22,824	4.3	21,062	4	488,358	92	532,244
Al-Qaseem	50,616	28	30,525	17	99,169	55	180,310
Eastern Region	73,263	32	135,039	58	23,607	10	231,909
Aseer	282,386	14	1,615,861	79	134,721	6.6	2,032,968
Tabouk	21,222	44	10,870	23	15,686	33	47,778
Hail	18,465	41	10,398	23	16,693	37	45,556
Northern Borders	6,783	49	4,011	29	2,917	21	13,711
Jazan	58,921	41	14,346	9.9	72,098	50	145,365
Najran	14,934	9.6	54,817	35	86,144	55	155,895
Al-Baha	25,759	39	28,872	44	10,795	16	65,426
Al-Jouf	9,986	23	7,016	16	27,087	61	44,089
Total	896,860	19	2,134,453	44	1,814,984	37	4,846,297

Alzamil (2014) claims that the availability of land suitable for residential development but not yet developed contributes to the increase of the price of a built property due to supply shortage. Additionally, undeveloped land contributes to the growth of squatter communities. The relative shortage of developed property that is not being used in this manner has aggravated the housing issue.

2.3.5.3. Current Construction Methods Issues and the Lack of Involving Recent Methods

These days many new methods and technologies are applied in the construction industry, especially in the building of homes (Alqahtany & Bin Mohanna 2019). The majority of these methods and technologies are done offsite, which means that work such as prefabrication, preassembly and modular building is not done on the construction site but in a factory (Alqahtany & Bin Mohanna 2019). There are several advantages of employing modern building methods; for example, defects, waste, health and safety hazards, cost, environmental effects, and time are all reduced (Alqahtany & Bin Mohanna 2019). Nowadays, in Saudi Arabia, the existing conventional construction methods have many disadvantages, including modification due to errors in construction, low-efficiency level of labour and time and an unqualified labour force (Assaf and Al-Hejji 2006). The efficiency of the housing delivery system is influenced by the duration of the regulatory approval procedure for construction projects (Makinde 2014).

Saudi Arabia's building sector continues to rely on inefficient processes, with home designs following a traditional and linear design process that is highly fragmented (Ahmed et al. 2019). Several homes are designed and built using unorthodox practices, such as hiring a building contractor to design and construct the house. Architects are typically not involved in the process, which saves money, resources and time because contractors have a variety of standard designs for houses, completed with drawings that can be altered to the client's needs (Ahmed et al. 2019). Moreover, nearly 70% of the country's buildings are not thermally insulated

(Alshahrani and Boait 2019). Every home is constructed with the same materials and envelope sections commonly accepted in the building industry (Ahmed et al. 2019).

2.3.5.4. High Cost of Construction

House prices in the Middle East, particularly in Saudi Arabia, have risen (Saud and li 2020). As a result of the increase in housing costs, moderate and low-income residents have difficulty affording a home (Jamali and Rahman 2016). According to several global and local research (Makinde 2014; Yates 2016; Assaf et al. 2010), one of the main obstacles to the availability of suitable homes for many clients is the high cost of construction. Alzamil (2014b) and Al-Hargi et al. (2004) mentioned that one of the factors of Saudi Arabia's high construction costs is the lack of specialised housing construction companies.

Furthermore, Saud and li (2020) stated that factors that influence housing costs in Saudi Arabia are high-interest rates on mortgages, costly technicalities of construction, costly construction procedures, socio-economic considerations of the Saudi Arabian population, high number of retirees with a sole intention of purchasing a house, challenges faced by private developers, failed government policies, lack of conformity of customer preferences with those of property developers and Inflation. Another study conducted by Assaf et al. (2010) discovered 34 reasons affecting the housing cost in Saudi Arabia. The result of the study illustrates that the top 10 reasons are as follows: insufficient labour availability, material standard, design quality, design modification, poor financial management on-site, lack of coordination, contract term, material cost, onsite disagreements, experiences of workers and long delays. Without a doubt, these factors have significant economic consequences for developers, which negatively impact the final pricing of housing units.

2.3.5.5. Environmental Challenges

In many housing markets across the world, the concern of sustainability is becoming increasingly significant (Mulliner & Algrnas 2018). The majority of Saudi Arabia's environmental issues come from the country's dependence on fossil fuels as a resource of energy for growth and development (Demirbas et al. 2017). Several industries in Saudi Arabia are responsible for greenhouse gas (GHG) emissions, but the electricity and heat, transportation and manufacturing and construction sectors are the most energy demanding and contribute the most amount of GHG emissions (Alajmi 2021). (Figure 2:12) illustrates the contribution of several sectors to greenhouse gas emissions in Saudi Arabia. In 2018, the contribution of Greenhouse gas emissions (GHG) of electricity and heat was 225.44 million tons, 136.02 million tons for transport and 125.12 million tons for manufacturing and construction. For industry, waste and aviation and shipping, GHG emissions were 96.75 million tons, 28.06 million tons and 21.94 million tons, respectively. Furthermore, GHG emissions for the fugitive emissions sector was 13.37 million tons and the agriculture sector was 6.31 million tons. Finally, GHG emissions for buildings and other fuel combustion were 5.08 million tons and 1.97 million tons, respectively (Ritchie and Roser 2020).

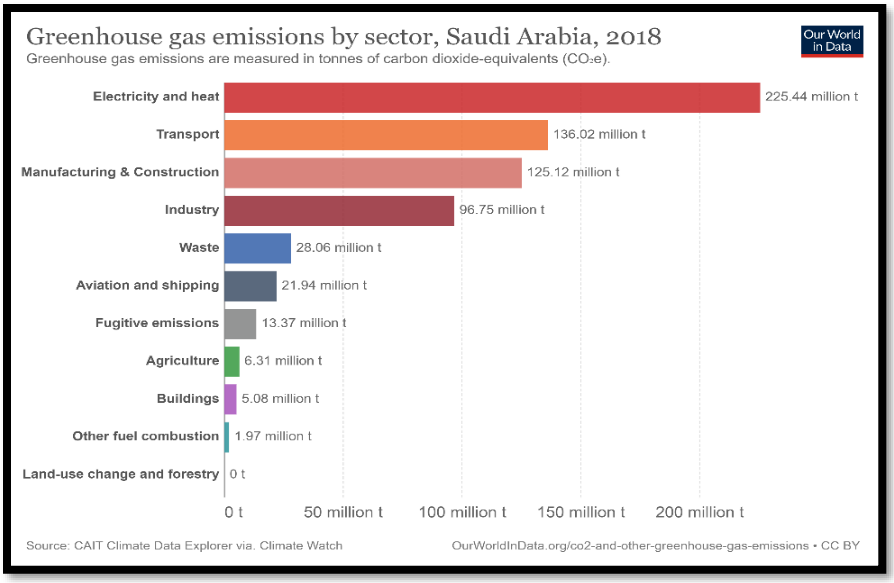

Figure 2-12 Greenhouse Gas (GHG) Emissions By Sector in Saudi Arabia in 2018.

When concentrating on the changes in the GHG emissions by sectors in Saudi Arabia from 1990 to 2018 for the first three sectors, it can be alleged that there was a huge jump in the GHG emissions. In the electricity and heat sector, the GHG emissions jumped from 71 million tons to 225.44 million tons, in transport from 49.4. million tons to 136.02 million tons and manufacturing and construction from 28.17 million tons to 125.12 million tons (Ritchie and Roser 2020). The capacity of Saudi buildings to battle GHG emissions in the future is significant, and due to the severely hot climate, people will certainly require much energy to make certain that they are comfortable in their indoor thermal environment (Abuhussain 2020).

Energy is consumed throughout the life of a building, from construction through decommissioning (Asif et al. 2017). The usage of energy throughout the building’s life cycle is both direct and indirect (Asif et al. 2017). Furthermore, the direct use of energy includes maintenance, renovation, operation, demolition, and construction of a building, while the indirect use of energy is associated with the installation of equipment and the production of materials employed in construction (Cabeza et al. 2014; Sartori & Hestnes 2007). The operating stage of a building contributes the most to its life cycle energy consumption. Energy consumption in the operating stage has been found to range from 40% to 90%, depending on several parameters such as user behaviour and climatic conditions (Hong et al., 2017; Guan et al., 2015).

Buildings in Saudi Arabia are becoming more dependent on artificial technologies to counteract the heat, such as air-conditioning, which requires a lot of energy to lower the temperature indoors and provide a pleasant thermal environment for people (Mulliner & Algrnas, 2018). Saudi Arabia's power use for air conditioning is responsible for more than 70% of the country's total electrical need (SEEC 2017). As a result, providing the highest level of thermal comfort while reducing the amount of energy needed by air-conditioning is difficult (Omer 2008). Also, by minimising the emission caused by energy consumption in buildings, greenhouse gases will be reduced and stable (Omer 2008).

Another issue confronting Saudi Arabia and other Arab nations is water shortage (Al Surf 2014). To meet the expanding demands of their people, several Arab countries have resorted to depending significantly on non-renewable groundwater reserves to supplement their restricted water supply (Swain 1998). Since the 1960s, the Gulf Cooperation Council countries (GCC) have seen massive growth in water demand and extremely restricted resources for conventional water, for instance fresh surface water and renewable groundwater, which has led to the adoption of alternative sources such as desalination and wastewater reclamation (Al Surf et al. 2013). Moreover, Saudi Arabia used roughly 10 million m3 of water in 1980, but this has grown significantly to 17.5 billion m3 in 2010 (Al Surf 2014). As a result, water conservation policies are essential in Saudi Arabia's construction sector to ensure the continued availability of natural freshwater sources and non-natural water sources obtained through saltwater desalination (Al Surf 2014).

As mentioned in Section 2.3.3., reinforced concrete is the most used construction system in Saudi Arabia (Bahammam 1998). (Table 2-4) presents the contributions of major sources to CO_2 emissions up till 2010 in Saudi Arabia. The table demonstrates that the industries that help produce reinforced concrete have a huge contribution to CO_2 emissions in Saudi Arabia (TNC 2016).

Table 2-4 2010 Carbon Dioxide (CO2) Emissions from Major Source Categories.

Source Categories	Percent of Total
Electricity Generation	31
Road Transport	21
Desalination	12
Petroleum Refining	8
Petrochemical Industries	7
Cement Production	5
Iron & Steel Production	4
Cement Industries	3
Agriculture	2
Fertilizer Industries	2
Others	5
Total	100

2.4. Saudi Arabia’s Vision 2030

“My first objective is for our country to be a pioneering and successful global model of excellence, on all fronts, and I will work with you to achieve that.” These words were said by King Salman Bin Abdulaziz Al Saud, custodian of the Two Holy Mosques (Saudi Vision 2030 2018). King Salman was the person who presented the Saudi Vision 2030, and Mohammad bin Salman bin Abdulaziz Al-Saud, crown prince and chairman of the Council of Economic and Development Affairs, is the engineer of this vision who satiated “a leader in providing opportunities for all through education and training, and high-quality services such as employment initiatives, health, housing, and entertainment” (Saudi Vision 2030 2018). The strengths of Saudi Arabia are that it is the soul of the Arab and Islamic world because of the two holy mosques, it is an investment powerhouse, and it is in a central location, connecting three continents.

Saudi Vision 2030 is a development process or strategy that assists the country in accomplishing its objectives while also ensuring its long-term prosperity. Saudi Vision 2030 focuses on diversifying its economy by focusing on health, education, infrastructure, tourist growth and recreation (Saudi Vision 2030 2018). Moreover, the vision has several specific goals, including creating a package of social-economic policies that are not dependent on oil exports. The goals are to create a long-term economic future for Saudi Arabia by improving its policies. In this study, the review of Saudi Vision 2030 will focus on the Saudi government's plans for housing.

The ministry of housing was founded in 2011 by a royal order (Ministry of Housing 2018). The Ministry of Housing's purpose is to implement programmes that encourage the public and private sectors to collaborate and partner in organising, monitoring and planning housing to enable housing with reasonable prices and good quality for all communities. Furthermore, the ministry's mission is to plan and promote a healthy, long-term housing environment. As a result of observing the Saudi Vision 2030 report on housing, The Ministry of Housing has produced many initiatives, programmes and policies to solve housing challenges for example the housing program (Sakani), Mullak, Etmam Developers Services Centre, Ejar services Network, Idle Lands Tax System, Developmental Housing, Sustainable Building, Saudi Real Estate Institute, Building Technology Stimulus initiative (BTSI), VAT Free for the First Dwelling, Real Estate Units Subdivision and Off-plan Sales or Rent Program (Ministry of Housing 2019). The following sections will discuss the most relevant initiative related to this study.

2.4.1. Housing Program (Sakani)

The Homes Program was established in 2018 as part of Vision 2030 to ensure that Saudi household’s access high-quality housing. Housing is a fundamental asset that has the power to shape and influence the liveliness of communities, families and society. Governments across the globe acknowledge the importance of housing, investing 0.1% – 1% of GDP to guarantee that their inhabitants have an entry to cheap and high-quality housing. Since its inception, the initiative has aimed to create new norms for the housing sector's growth, allowing individuals to choose from various housing alternatives. The percentage of households in Saudi Arabia that own homes will rise due to this assistance. According to the housing policy, the percentage of homeownership will reach 70% by 2030 and achieve financial sustainability.

Saudi Arabia follows the worldwide trend in housing policy and raises the standard by making the growth of the residential market mainly, housing access, a primary goal of the vision’s strategy. Vision 2030 may immediately enhance the quality of life for Saudi families through the Program by expanding access to cheap, high-quality, safe and well-located housing. In addition, because our cities' design, density and connectivity are dependent on the housing sector, the Program indirectly contributes to several additional vision objectives. It will grow to be a significant engine of urban development. Finally, the programme will increase the sector's attractiveness to private sector investment to promote the sector's stability and long-term sustainability under various economic scenarios.

2.4.2. Sustainable Building Initiative

The Ministry of Housing is looking for a variety of initiatives and solutions to help it meet its goals of raising citizen ownership of residential units and managing the real estate market. As a result, the ministry established the sustainable building platform, which seeks to provide a set of resources that contribute to the long-term viability of housing units, including:

- Building Quality Check

The building quality inspection service aims to allow the recipient adjacent to the construction (whether individuals or real estate developers) to validate the safety and quality of construction processes through an examination mechanism by specialised examining engineers, with the housing unit receiving a structure quality certificate after all stages of the inspection are successfully approved.

- Prefab Inspection

The purpose of the prefabricated building inspection service is to allow individuals who want to buy or rent a building to confirm its safety and quality. This is accomplished by trained engineers using a visual inspection method to discover visible flaws in prefabricated structures. After the examination, a report is made and given to the individual regarding the condition of the house.

- Sustainability Assessment Service

It is a service that allows for measuring a building's sustainability by adhering to the environmental criteria that increase the building's efficiency, improve the quality of life inside the structure and reduce the environmental effect of construction materials and waste. This effort establishes sustainable criteria that increase a building's efficiency by awarding points for each requirement achieved. The total points determine the building's sustainability, after which it is awarded a certificate. Furthermore, the sustainability assessment service benefits include:

- Increasing the indoor quality of living.
- Improving the efficiency of water and energy consumption.
- Enhancing the level of waste recycling management by households.
- Reduction of maintenance costs.
- Enhancing building operation management.
- Reducing the environmental pollution outside and inside the building.
- Establishing the philosophy of sustainability in society.

2.4.3. Building Technology Stimulus Initiative (BTSI)

The Building Technology Stimulus Initiative (BTSI) was created with the regard to Vision 2030's need to transition the housing industry from conventional to modern construction. The Logistics Program, National Industrial Developments, the Private Sector Stimulus Plan and Housing Program are encouraging and overseeing (BTSI). BTSI's mission is to create future housing units that are sustainable, inexpensive and smart. Moreover, BTSI established a cumulative aim of expanding dwelling units by utilising construction technology by 2023, as indicated in (Figure 2-13). This goal is ambitious because it is predicted that building technology would be used in 50% of the total 680000 dwelling units. BTSI's purpose is to solve the affordable housing need gap in Saudi Arabia by promoting the use of new innovative technologies in the construction sector. The objectives of BTSI are:

- Decrease the time it takes to build residential units to increase housing output.
- Make construction more of a source of value-added jobs for Saudi nationals.
- Decrease the cost of building a single home to make it more affordable.
- Improve the construction quality of residential dwellings.

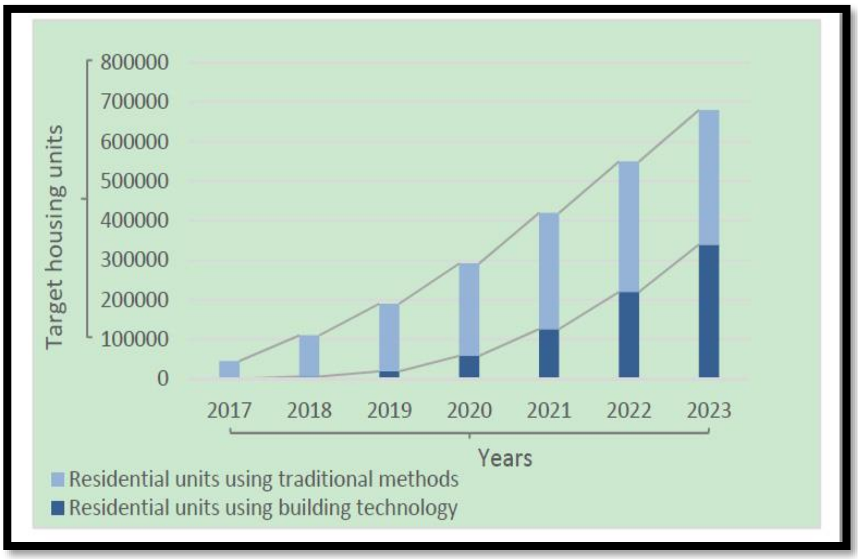

Figure 2-13 Expanding the Use of New Technologies for Housing Delivery (BTSI 2019).

Over time, construction methods have been refined to satisfy human demands with high standards and quality at a fair cost. There are also a variety of unique ways that have been applied across the world. The following are the most common forms of construction technologies adopted by the BTSI in Saudi Arabia:

- Insulated Precast Systems.

A concrete wall manufacturing technology that uses prefabricated moulds off-site.

- Autoclaved Aerated Concrete.

A light-weight precast concrete containing air bubbles that produce a lightweight and low-density material.

- Insulated Concrete Forms.

Extended polystyrene blocks stacked and then filled with concrete.

- Tunnel Formwork.

Stacks of expanded polystyrene blocks filled with concrete.

-Structural Light Gauge Steel.

Cold-formed steel panels manufactured at the factory and transported to the site for installation.

- 3D Printing Technology.

The most recent generation of technologies for current construction processes is 3D printing. This technique is primarily based on computer-assisted work, which constructs the ceilings and walls with the consideration of plumbing pipes and electrical installation. Also, it has the advantage of doing all the processes without the interference of humans.

2.5. 3D Printing Technology.

2.5.1. Additive Manufacturing and 3D Printing.

The phrase "additive manufacturing" (AM) refers to a variety of digital "layer by layer" production processes (Almerbati 2016). Additive manufacturing is defined by The American Society for Testing and Materials (ASTM) as the procedure of forming a three-dimensional solid object layer by layer using a computer-aided design (CAD) digital file to produce any shape (Wohlers Associates 2016). Furthermore, as seen in (Figure 2-14), AM is divided into three methods: Rapid prototyping (RP), Rapid manufacturing (RM) and Rapid tooling (RT) (Strauss 2013). This process can be done using different materials and different printing technologies such as nozzle head poring. The term 3D printing is referred to as additive manufacturing (Gao et al. 2015).

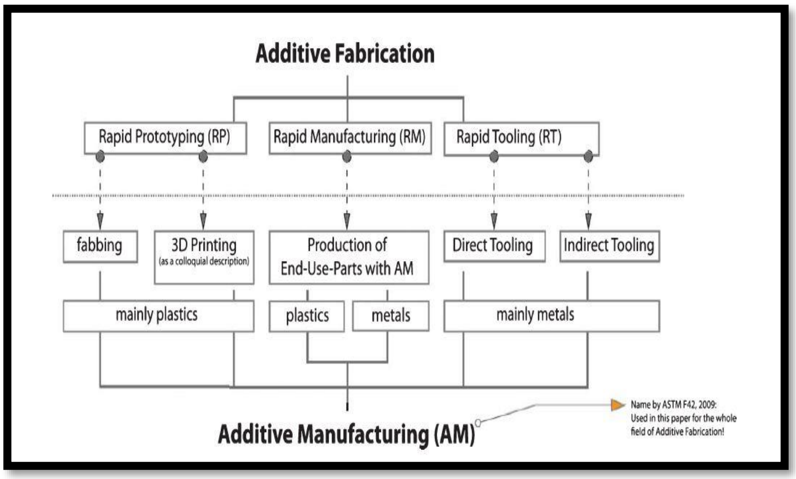

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Figure 2-14 Manufacturing AM Methods (Strauss 2013).

According to ISO and ASTM, (Wohlers Associates 2016), the official word for the industry is additive manufacturing, however, the phrase "3D printing" has grown more common than AM. Wohlers Associates (2016) state that when referring to AM technology and the sector it represents, the mainstream press, CAD industry and investment community use the term "3D printing." Moreover, 3D printing uses a range of materials, equipment, and procedures that are developed over time and have the possibility to revolutionise manufacturing and logistics processes (Ngo et al. 2018). 3D printing technology is now applied in a variety of industries, involving research, the military, architecture, the computer business, the medical industry, construction, education, engineering, and fashion. Even with the advantages of 3D printing, including automation, flexibility in design, and reducing waste, the adoption of 3D printing in the construction industry has been slow and limited (Ngo et al. 2018).

2.5.2. Additive Manufacturing vs Subtractive Manufacturing

It is still premature to declare that 3D printing will supplant subtractive manufacturing as a manufacturing technique. Though, a thorough grasp of the advantages of 3D printing over subtractive tooling would help to clarify this debate (Almerbati 2016). Subtractive manufacturing is used in most traditional manufacturing processes. Subtractive processes include honing, machining, drilling and milling, which entail removing materials from a construct source (Liu 2017). According to Almerbati (2016), subtractive techniques provide greater part dimension accuracy and better surface finishes than additive manufacturing. To get final results, the traditional subtractive process will frequently necessitate the use of specialised equipment.

When compared to the injection moulded techniques, Berman (2012) claims that 3D printing is more cost-effective and faster. If metal or powder is applied, 3D printing may save money on expensive moulds and allow for the recycling of up to 98% of waste material. Due to the nature of the production process, personalised products may be produced on a budget and in a short amount of time. Furthermore, the benefit of sharing and updating the design is to have new capabilities and forms that are hypothetically limitless.

The fact that AM is an additive rather than subtractive process highlights the necessity to spend time putting the existing pieces together and assures that AM is a topic worth exploring and anticipating (Soar and Andreen 2012).

2.5.3. History of 3D Printing Technology

Year after year, fast expansion drove this industry, not only in terms of AM technology, but also in terms of materials, bed size and time spent. Charles Hull was the inventor of 3D printing Stereolithography (SLA) in **1983** (Sakin and Kiroglu 2017). During his job at Ultraviolet Products, a company that makes protective coatings in Southern California U.S.A., Hull started experimenting with 3D printing in **1983**. He invented a system for layering curable resin layer after layer into particular shapes to be used as plastic models (Prince 2014). A little teacup was the first 3D item to be produced (Mu 2016). Hull used the term "stereolithography" to describe the first 3D printing process, and after obtaining a patent, 3D Systems was established to manufacture and advertise commercial 3D printers (Balletti et al. 2017). Moreover, in **1986**, the concept of selective laser sintering (SLS) was formed at the University of Texas at Austin's Mechanical Engineering Department by Carl Deckard and Joe

Beaman, and they got it patented (Ramesh et al. 2018; Ramya et al. 2016). In **1988**, the fused deposition modelling was invented and patented by Scott Crump, which employs fused and melted material to build a model layer by layer. After the invention, Crump established Stratasys, a huge company of 3D printing equipment (Balletti et al. 2017). The usage of modern 3D printers to make metal parts started in **1990** (Das et al. 2016). Bourell used a laser to put together a copper-solder mix to make a metal part in **1990** (Das et al. 2016).

Later in 1991, three technologies were commercialised, including solid ground curing (SGC) from Cubital, fused deposition modelling (FDM) from Stratasys, and laminated object manufacturing (LOM) from Helisys (Wohlers Associates 2016). In 1993, Yamamoto and Sakai, who worked for a Japanese company called Toho Titanium at the time, came up with the idea of Electron Beam Melting (EBM) (Das et al. 2016). In 1997, In an alliance with Chalmers University of Technology CUT in Gothenburg, Sweden's Arcam AB developed powder-bed metal 3D printing using an electron-beam power source. Binder jetting technologies was first launched in 1998, and the Ex One Company was established. The metal printing industry was the target market for these devices (Das et al. 2016). In 2001, the ultrasonic consolidation method was marketed by Solidica (Das et al. 2016). The first machines were delivered in early 2002 (Das et al. 2016).

In 2002, EBM S12 was introduced as the first production model manufactured using Powder-bed metal 3D printing (Das et al. 2016). Dr. Behrokh Khoshnevis who works at the University of Southern California created the Contour Crafting System which is a gigantic 3D printer that be able to manufacture structures in situ in 2006. It operates similar to a 3D printer desktop, except it prints using a gantry to structure building parts utilises concrete (Afsha 2018). D-shape was founded in 2007 and was regarded as the world's first large-scale 3D printer at the time (Lowke et al. 2018).

2.5.4. Principles of 3D Printing Technology.

Inkjet or classic laser printers function similar to 3D printers (Berman 2012), except that 3D printers build up a 3D object by printing layer by layer of different materials such as metal, plastic, concrete, or any other materials on top of each other, while inkjet printers print two dimensional (2D) content on a piece of paper (Berman 2012; Dolinsky 2014). The 3D printing process starts with creating the model or the design using CAD software (Gao et al. 2015). After that, the file is converted into an industry-standard format such as STL, 3DS, IGES, COLLADA and STEP file type (Smith 2009). As we know, all 3D printing devices print layer by layer and the converted file needs to be split into layers before sending it to the printer, which is known as slicing (Kwok et al. 2017; Gao et al. 2015). Subsequently, after the sliced file has been processed (G-code file), a file containing instructions will be sent to the printer to construct the generated part (Moore et al. 2016). Based on the location and orientation of the component in the printing equipment, G-code will frequently use algorithms to identify where and when supports are required (Aguilera Jr 2016), see (Figure 2-15). Although the printing process is the same "layer by layer", the printing type varies depending on the methods and materials used, which will be discussed further in the literature such as Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), and Laminated Object Manufacturing (LOM).

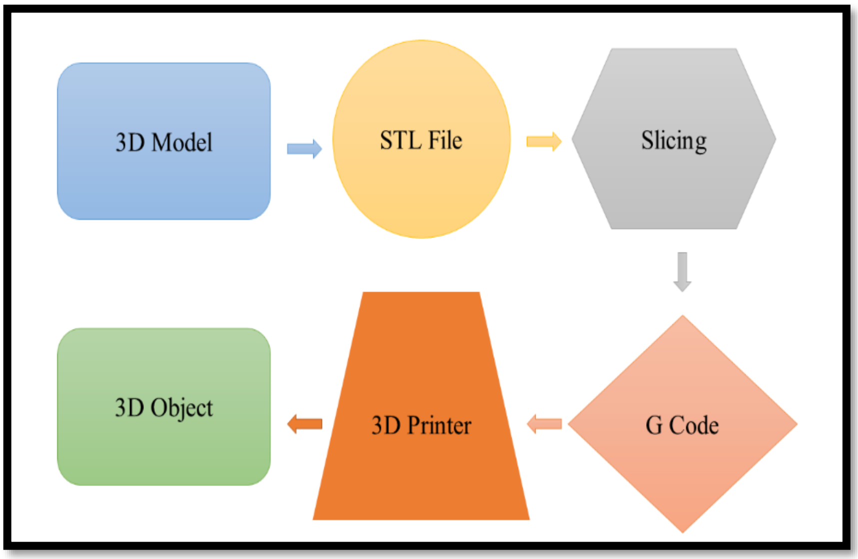


Figure 2-15 Workflow of 3D Printing Process Source (Siddique et al. 2019).

2.5.5. 3D printing Technologies

While 3D printing is a process of adding material during construction layer by layer, some varieties of technologies have been developed through the years with different functions (Shahrubudin et al. 2019). A document to define a standard terminology for AM was issued by the International Organization for Standardization (ISO) in collaboration with The American Society for Testing and Materials (ASTM) International (ASTM 2016). In this document, AM was divided into seven different processes that involve binder jetting, materials jetting, materials extrusion, powder bed fusion, directed energy deposition, sheet lamination, and vat Photopolymerization.

- Binder Jetting

Binder jetting is a rapid prototyping 3D printing process that deposits a liquid binding agent selectively on each layer towards binding powders together (Shahrubudin et al. 2019). MIT was the primary developer of Binder jetting in a process called 3D printing (3DP) (Gibson et al. 2021). The procedure of binder jetting is considered to be inexpensive, fast and, simple as powder particles are bonded together. Additionally, it has the capability of printing large products (Shahrubudin et al. 2019).

- Materials Jetting

Materials jetting is considered as a 3D printing process that extrudes drop by drop liquid material that solidifies to form the needed shape (Shahrubudin et al. 2019). Simultaneously, material jetting produces very high dimensional accuracy and a smooth surface finish (Tofail et al. 2018). Furthermore, materials such as composite, biologicals, polymers, hybrids and ceramics can be used in material jetting (Tofail et al. 2018). An example of this process is PolyJet technology from Stratasys (Gibson et al. 2021).

- Materials Extrusion

Materials extrusion is a 3D printing process that extrudes material via a nozzle and places it layer by layer on top of a substrate (Delgado Camacho et al. 2018a). The earliest illustration of a material extrusion system is Fused deposition modelling (FDM) (Shahrubudin et al. 2019). FDM was founded in early 1990 by Crump and it was commercialised by Stratasys (Gibson et al. 2021; Stansbury and Idacavage 2016).

Moreover, materials extrusion is considered to be the most commonly known process (ASTM 2016).

- Directed Energy Deposition

Directed energy deposition is the procedure of focusing thermal energy sources such as electron beam or laser to melt materials for the duration of the deposition (Tofail et al. 2018). An example of this process is Laser engineered net shaping (LENS), which was created at Sandia National Laboratories (Huang et al. 2015; Gibson et al. 2021). LENS is mainly useful for repairing damaged metal parts (Mudge and Wald 2007).

- Powder Bed Fusion

Powder bed fusion is the procedure of using a laser or electronic beam to fuse or melt fuse the material powder together (Shahrubudin et al. 2019). It includes selective laser sintering (SLS), selective heat sintering (SHS), and electron beam melting (EBM) printing techniques (Shahrubudin et al. 2019). Moreover, SLS is considered to be the primary example of powder-based 3D printing technology that was developed at the University of Texas at Austin's Mechanical Engineering Department by Carl Deckard and Joe Beaman (Ramesh et al. 2018; Ramya et al. 2016). To generate a 3D product, SLS uses a high-power laser to sinter polymer powders (Tiwari et al. 2015). Meanwhile, another technique to create a 3D printing product is the SHS technique which uses thermal head printing to melt thermoplastic powder (Rajamani and Balasubramanian 2019). Finally, EBM uses an energy resource to warm up the material (Lunetto et al. 2020).

- Vat Photopolymerization

Vat Photopolymerization is the process of using ultraviolet (UV), light or laser to cure a liquid light-activated polymer to form an object (Low et al. 2017). Stereolithography (SLA) is the most common technique, which uses an ultraviolet (UV) laser to trace and cure the model's cross-section, while the rest area remains in liquid form until the trace and cure are completed. The part will be coated with a new layer of resin after the platform is lowered (Low et al. 2017). Digital light processing (DLP) is a similar technique to SLA. The differences between them are that DLP uses a light source, and it is used for the whole surface (Schmidt and Colombo 2018; Shahrubudin et al. 2019). Initially, the liquid is the main material used in this process, and when subjected to ultraviolet light, it solidifies (Tiwari et al. 2015). The time of exposure, wavelength, and the amount of power source are the important boundaries of Vat Photopolymerization (Shahrubudin et al. 2019).

- Sheet Lamination

Sheet lamination is the process of forming and bonding objects using different materials such as sheets of plastic or paper (Frketic et al. 2017). An example of sheet lamination is Ultrasound additive manufacturing (UAM), which was commercialised by Solidica Inc (Tiwari et al. 2015). This process requires the welding of metal plates by applying a normal force to a roller as it moves over metal plates whilst performing ultrasonic vibration (Sridharan et al. 2016). Furthermore, another example is laminated object manufacturing (LOM), which was developed by Helisys Inc (Shahrubudin et al. 2019). LOM allows complicated geometrical parts to be manufactured by attaching sheets of rolled material and cutting the unwanted parts via a tool that is driven by a simple numerical control (Olivier et al. 2017). The benefits of Sheet lamination are that it is relatively inexpensive, has the ability to do full-colour prints and the materials used in the process are easy to handle and can be recycled (Shahrubudin et al. 2019).

As Conner et al. (2014) assert, each of these technologies has its own potential impact on the processing capabilities, volume building, product quality, speed and materials, and also its own advantages and limitations. Also, the previous processes have been explored in many various areas for instance medical, food, aerospace, construction, automotive, and electric (Parupelli and Desai 2019). 3D printing technologies in the construction industry are considered to be in an early stage of development and innovation diffusion, and use more than one process including binder jetting, direct energy deposition, powder bed fusion, and material extrusion

(Delgado Camacho et al. 2018a). Moreover, initial applications mainly focused on material extrusion processes for large-scale elements (Delgado Camacho et al. 2018). To adjust to the need of the construction industry, other 3D printing technologies have also been developed in recent years, using different materials such as polymer, metallic, cementation and composite (Wu et al. 2016; Delgado Camacho et al. 2018). D-Shape, Concrete Printing, and Contour Crafting (CC) are the main technologies that the current printing procedures are targeting in architecture and construction (Ma et al. 2018). CC is an additive fabrication technology developed at the University of South California (Zareiyan and Khoshnevis 2017). To create precise and smooth flat and freeform surfaces, CC employs computer control to take advantage of towelling's exceptional ability to form surfaces (Khoshnevis and Bekey 2017). CC is used in a gantry system that carries a nozzle that moves on a parallel lane installed at the construction site (Zareiyan and Khoshnevis 2017). Furthermore, the CC process combines a filling and an extrusion process that is attached to the nozzle to extrude cement-based material layer by layer (Figure 2-16) (Lim et al. 2012; Ma et al. 2018). Furthermore, the main challenge of CC is retaining the uniform level of viscosity, which will enable a smoother surface finish and enhanced structural strength (Khoshnevis and Bekey 2017).

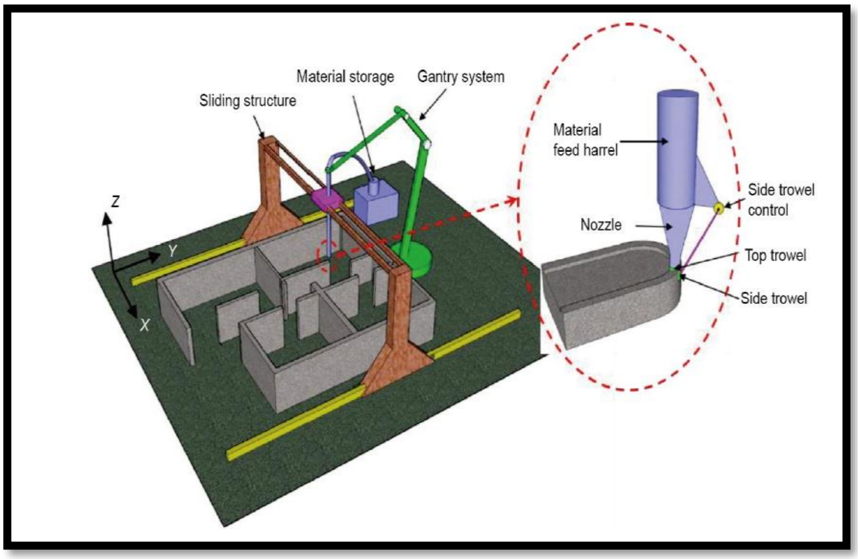


Figure 2-16 Contour Crafting (CC) (Ma et al. 2018).

D-shape is a 3D printing process that uses layers of adhesive and powder instead of cement which is used in other processes (Zhang et al. 2019). When D-shape was first created in 2007, it was considered to be the first large scale construction printer (Lowke et al. 2018). Like the usual 3D printing process, D-shape includes selectively hardened powder using a binder (Perkins and Skitmore 2015). Moreover, D-shape allows for the production of full-size buildings without the need for human involvement by using binder and sand to produce a stonelike freeform structure. (Figure 2-17) (Tibaut et al. 2014). The core system of the D-shape is the printing head, which at the beginning of the printing process works as a solid material spreader figure (Cesaretti et al. 2014).

Figure 2-17 D-shape (Sher 2015).

Concrete Printing is a 3D printing process that was established by the research team at the Loughborough University (Lim et al. 2012). This process is similar to Contour Crafting (CC), which uses the extrusion of cement mortar (Figure 2-18) . (Wu et al. 2016). Concrete Printing allows for greater control of external and internal geometries because the technology has a smaller resolution of deposition compared to CC, and the printing speed in CC is higher (Zhang et al. 2019).

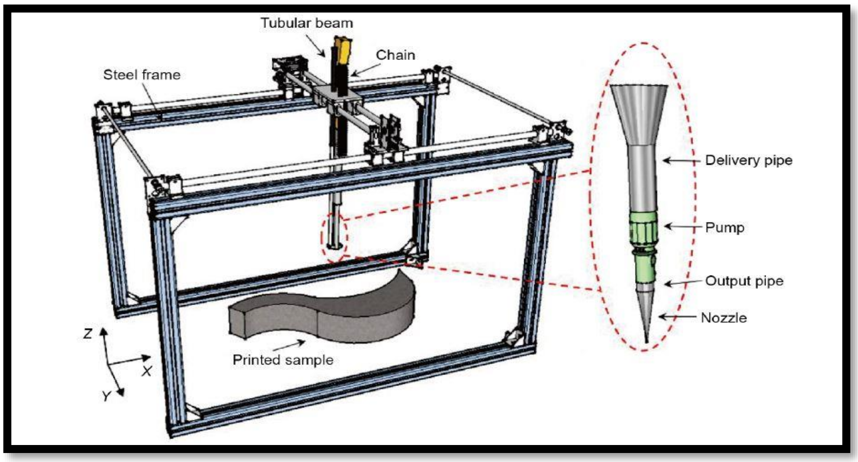


Figure 2-18 Concrete Printing (Ma et al. 2018).

Through the years, other companies developed new and enhanced 3D printers such as CyBe Construction, Apis Cor, WinSun company, C-Fab from Branch technology, MX3D, BAAM and COBOD. Furthermore, most technologies use a gantry system to deliver materials (Delgado Camacho et al. 2018). Gantry systems are based on the cartesian coordinates system, where the nozzle moves in three axes (X, Y, Z) (Figure 2-19). (Zhang et al. 2018). Another technology that is used for 3D printing is small robots with a specific task such as MiniBuilders. Also, some companies use robotic arms such as ABB and CyBe (Figure 2-20). The robotic arm moves in six axes, which gives more flexibility for the work and takes less space (Delgado Camacho et al. 2018).

Figure 2-19 COBOD 2 Printer (COBOD 2020).

Figure 2-20 CyBe RC 3D Printer (Clarke 2016).

2.5.6. 3D Printing Technology on a Large-Scale Construction

Large-scale AM has been developed in recent years to fulfil the demands of the design and construction sectors (Ma et al. 2018). The competition to employ 3DP in architecture has been heating up. The concept is generating novel solutions every day, from modular homes, bridges, and construction parts. Furthermore, Wohlers Associates' (2016) report states that architectural applications account for just 3% of the whole AM industry. However, this sector is currently developing., since it was only employed in 2014 for residential constructions, and it has demonstrated tremendous promise since then (Ngo et al. 2018). In recent years, automated construction using 3D printing has received a lot of attention (Lee et al. 2019). Following are some examples of 3D printed projects from around the world.

- WinSun Company Buildings

In 2014, the Chinese construction company WinSun claimed that they managed to print 10 houses in less than 24 hours in Shanghai (Sanjayan and Nematollahi 2019). The materials were extracted from a nozzle, layer by layer by using a gigantic printer 150 m long, 10 m wide and 6.6 m high, with modified concrete and construction waste as the project's main materials (Hager et al. 2016). Regrading reinforcing and insulation of the walls, a diagonal pattern and hollow structure were used (Geneidy and Ismaeel 2018). Each of the 10 houses cost approximately $4,800 (Figure 2-21). One year later, WinSun built a five-storey building using the same technique that was used for the 10 houses. To the date of the building's establishment, this building is believed to be the biggest printed building in the world (Figure 2-22).

Figure 2-21 10 Houses Were Built in 24 Hours Using 3D Printing.

Figure 2-22 The Tallest 3D Printed Building in the World.

Furthermore, according to Dalton (2016), the 3D-printed office building in Dubai was the first 3D-printed building in the world and was also constructed by the WinSun company. The one-story building is 2,700 ft and was built in just 17 days for $140,000, which covered the 19 workers, construction material, electricians and mechanical engineers. As such, the cost of the construction and labour was almost half the price of conventional construction. It was constructed with a 20-foot high printer almost two storeys tall, 120 ft long and 40 ft wide. It only required one worker to control it, with the other 18 working on the installation, electrics and mechanical work. The material used to build this project was a special mix of fibre-reinforced gypsum, concrete and fibre-reinforced plastic (Kira 2015) (Figure 3-23). According to Wam (2016), the United Arab Emirates' Minister of Cabinet Affairs stated that by 2030, 25% of the buildings in Dubai will be built via 3D printing.

Figure 2-23 The 3D Printed Office Building in Dubai (Busta 2016).

- The world's First 3D Printed Family House

In 2018, Nantes, France, was considered to be the first place in the world to contain a 3D printed house. The single-storey building, comprising four bedrooms and one large 95 m (1022 ft) room in the centre was built in 54 hours, but it took approximately four months to install the windows, roof and doors. Each wall consists of two polyurethane insulator layers separated by a space filled with cement. As a consequence, the wall becomes thick, insulated, and durable (Figure 2-24). The cost of the building was almost £167,000, which was 20% less than the conventional method. The team who worked on this project believe that they could finish printing the same house again in 33 hours (Cowan 2018).

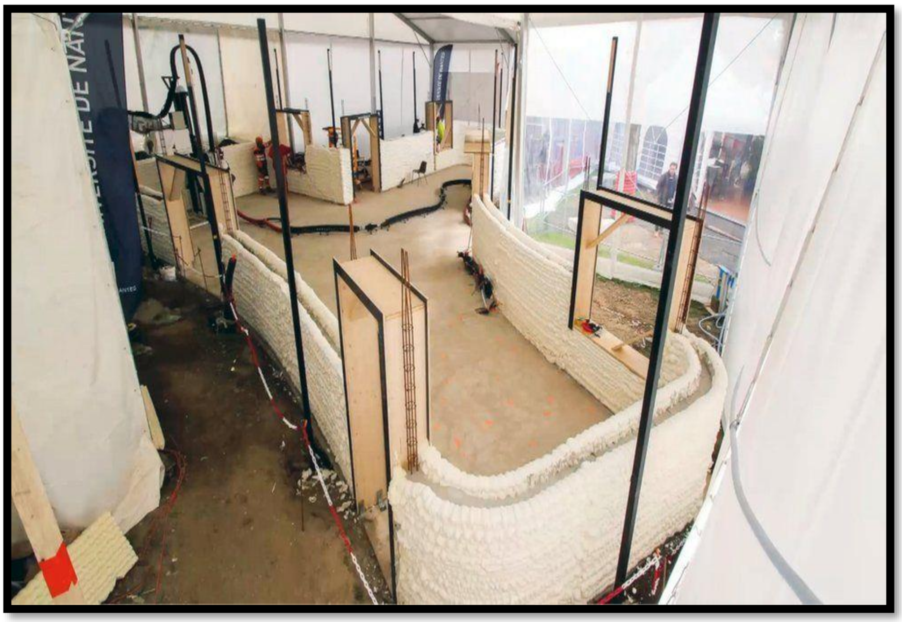


Figure 2-24 The World's First 3D Printed Family House (Cowan 2018).

- Saudi Arabia's First 3D Printed House

Saudi Arabia constructed the first 3D printed house in Riyadh in 2018. The National Housing and Industrial Development and Logistics Programme states that the Saudi government is willing to adopt new technology in construction so it can accommodate its new vision. By 2030, the government is prepared to have 1.5 million 3D printed houses across the country. The project was undertaken by a Dutch company called CyBe and comprises one floor with an area of 80 sq m (Ministry of Housing 2018; CyBe 2018). This project uses a mobile robotic arm placed on a caterpillar for the printing process. Furthermore, 3D printing concrete was used as the main material for this project and bearing walls and a roof system of hollow core slabs was the structural system recommended by CyBe. The project was constructed in a week and was presented as a showcase for 3D printed residences (Figure 2-25). Furthermore, the cost of the house wasn't revealed to the public or the press. Overall, the house's onsite printing took one week to complete (Ministry of Housing 2018; CyBe 2018).

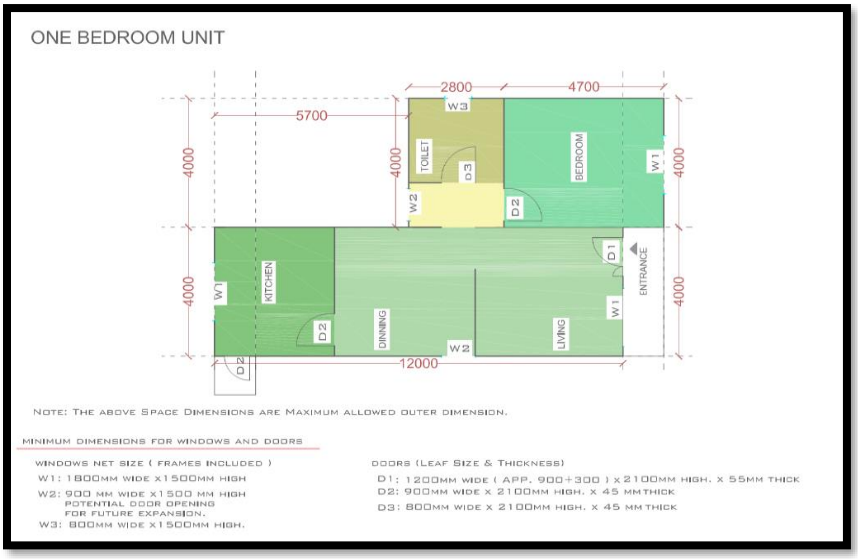

ONE BEDROOM UNIT
2800
4700
5700
4000
4000
4000
4000
W3
TOILET
D3
BEDROOM
W1
W2
D2
D1
ENTRANCE
W1
KITCHEN
D2
DINNING
W2
LIVING
W1
D2
12000
NOTE: THE ABOVE SPACE DIMENSIONS ARE MAXIMUM ALLOWED OUTER DIMENSION.
MINIMUM DIMENSIONS FOR WINDOWS AND DOORS
WINDOWS NET SIZE (FRAMES INCLUDED)
W1: 1800MM WIDE X1500MM HIGH
W2: 900 MM WIDE X1500 MM HIGH
POTENTIAL DOOR OPENING
FOR FUTURE EXPANSION.
W3: 800MM WIDE X1500MM HIGH.
DOORS (LEAF SIZE & THICKNESS)
D1: 1200MM WIDE (APP. 900+300) X 2100MM HIGH. X 55MM THICK
D2: 900MM WIDE X 2100MM HIGH. X 45 MM THICK
D3: 800MM WIDE X 2100MM HIGH. X 45 MM THICK

Figure 2-25 3D Printed House in Saudi Arabia (Ministry of Housing 2018).

- Andrey Rudenko

In 2014, Andrey Rudenko used Contour Crafting 3D printing technology to construct a concrete castle utilising a mix of sand and cement. it was printed completely in a one shot apart from the towers, which have being printed individually and afterword's assembled onto the castle (Alec 2015) (Figure 2-26).

Figure 2-26 3D Printed Concrete Castle (Rudenko 2015).

After the success of the castle project, a partnership was made between the Lewis Grand hotel in the Philippines and Andrey Rudenko to print the number one 3D hotel in the world. The hotel was ultimately printed on a 130 m2 party room, comprising a living room, several double bedrooms and a Jacuzzi. The material used in this project had a specific type of sand and volcanic ash to enhance and increase the strength and bonding between the printed layers (Rudenko 2015; Alec 2015) (Figure 2-27).

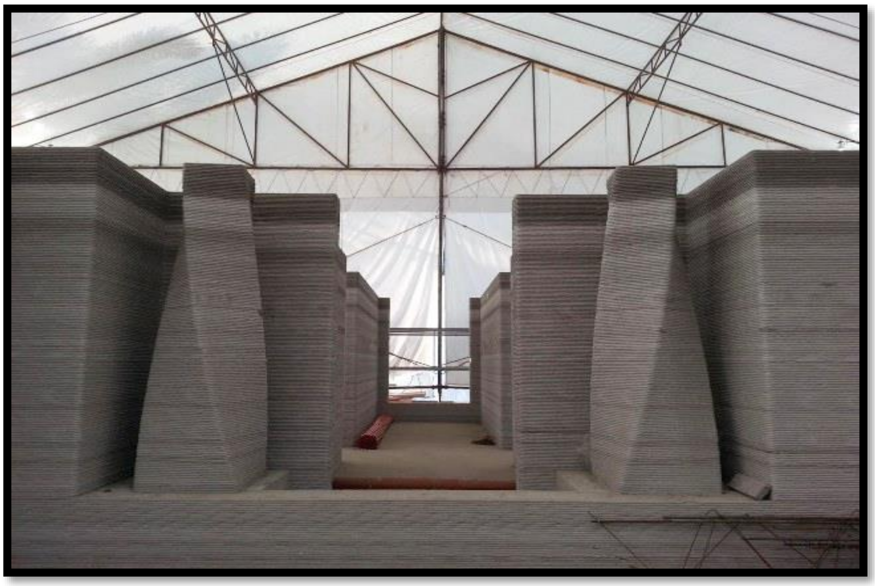


Figure 2-27 3D Printed Hotel (Rudenko 2015).

- Apis Cor 3D Printed Buildings

This project was undertaken in 2017 by Apis Cor, a well-known company in the field of 3D printing. The project was a one-storey house of 38 m2 in Stupino, Moscow, Russia. This project was made special by the fact that the house was printed onsite rather than offsite, and merely assembled onsite. The project was covered by a tent to protect the printing job from the outside temperatures. Moreover, the company took advantage of the flexibility of the 3D printing technology and made an unusual design rather than an ordinary one. Specifically, Apis Cor revealed that the project cost $10,134, and took only one day to complete. Meanwhile, geopolymer cement was used as the printing material. This material is made of fly-ash and slag and produces 90% less CO_2 emissions than the emissions produced by Portland cement. Furthermore, geopolymer cement has other benefits in addition to being environmentally friendly, such as the ability to enhance 50% of its strength after the first three days, excellent fire resistance and thermal insulation (Garfield 2017) (Figure 2-28).

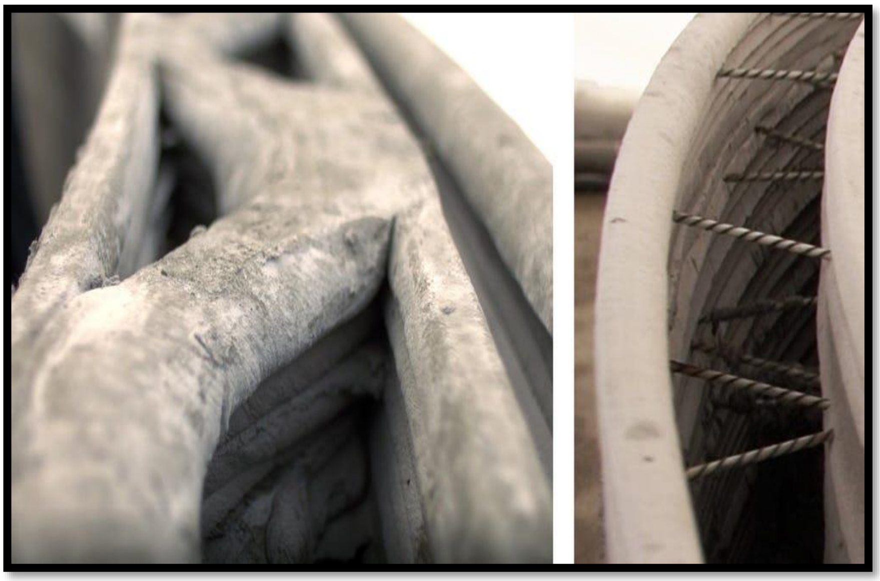


Figure 2-28 Apis Cor 3D Printed House (Garfield 2017).

Recently, in 2019, Apis Cor completed the largest 3D printed building in the world in Dubai. The two-storey administrative building, having a height of 9.5 meters and an area of 640 square meters, was done for Dubai Municipality. Apis Cor managed to do the whole printing process onsite using their latest technology of 3D printing. Furthermore, the printing process took place in an open area, which means that environmental requirements for the printed material such as humidity and temperature were not controlled. The structural analysis and calculation were prepared by the Moscow State University of Civil Engineering. This included structural model, vertical action, internal forces, accidental torsion effects, seismic actions, damage limitations, shear forces, displacements, modal analysis, floor masses and mass moments of inertia (Apis Cor 2019). As mentioned earlier, this project is part of the United Arab Emirates' vision of having 25% 3D printed houses in Dubai by 2030 (Busta 2016) (Figure 2-29).

Figure 2-29 Apis Cor Largest 3D Printed Building.

- ICON 3D Printed Houses

New Story and ICON revealed the first 3D printed house that was built in Austin, Texas, USA. The ICON team stated to have established a method for 3D printing a 55 square meter house for a total of $4000 in less than 24 hours. Furthermore, the printer that was used in this project is called the Vulcan, which was designed to work under unpredictable limitations such as limited power and water. The printing process was only used for the walls, while the roof was constructed using steel and wood in the traditional method. Subsequently, the goal of this project in the next 18 months is to build such houses in El Salvador, whereby through partnerships, the production of these houses could be replicated in other communities (ICON 2018; Michelle 2018) (Figure 2-30).

Figure 2-30 The first 3D Printed Home in America (Michelle 2018).

- COBOD 3D Printed Projects.

One of COBOD's 3D building printers was used to build the first house on the German land in North Rhine-Westphalia. The two-storey single-family home has a living space of roughly 160 square metres. The structure is made up of triple-layer cavity walls with insulation (Figure 24). PERI benefits from using CBOD2 in 3D printing construction because it saves time, simplifies the building processes and lowers the prices. The skilled labour shortage is a global issue that PERI is attempting to address with COBOD's 3D printing technology. From an architectural and design aspect, this project has set new benchmarks on a worldwide scale (Beckum 2021; PERI 2021) (Figure 2-31).

Figure 2-31 Two-Story Residential Building in Germany (Beckum 2021; PERI 2021).

Following the completion of the first two-story residential structure, PERI adapted BOD2 to an even larger construction project—the first 3D printed three-story building in Europe. The 380m2 building is composed of three stories and five apartments in total. The BOD2 in use measured 12.5 m × 20 m x 10 m, which is equivalent to a 5-8-4 printer size. The multi-family home's first occupants moved in in August 2021. With projects this large passing German building code rules, COBOD states they are extremely pleased of the fact that they can no longer be questioned. (Wallenhausen 2021; PERI 2021) (Figure 2-32).

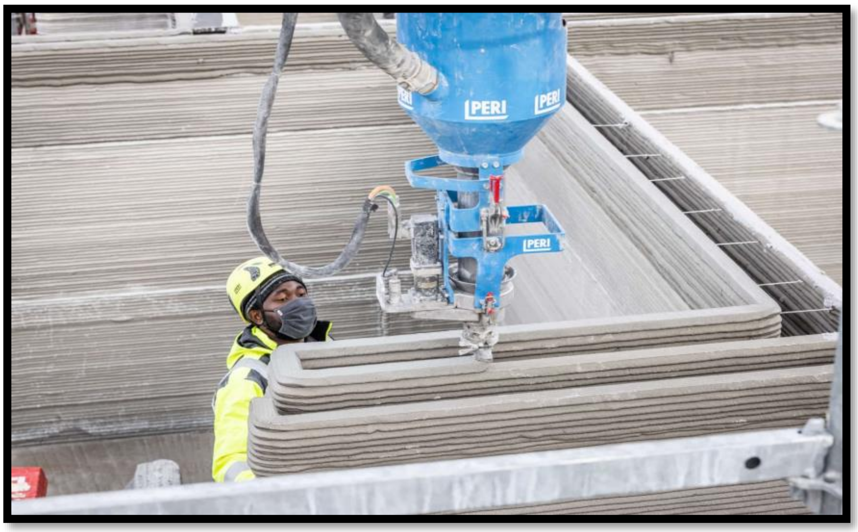


Figure 2-32 Europe's Largest 3D Printed Apartment Building (PERI 2021).

2.5.7. Materials in 3D Printing Technology

Like any manufacturing process, the used materials in 3D printing must have certain specifications to be compatible with the technology (El-Sayegh et al. 2020). ASTM (2016) categorises the used materials in 3D printing as concrete, polymer, metallic and composite. Furthermore, 3DP concrete is more advanced and commonly used in construction than polymer or metal printing (Buchanan and Gardner 2019). 3DP has been used to construct a number of pedestrian bridges and office and residential buildings (Buchanan and Gardner 2019). 3DP is one of the quickly evolving fields, as evidenced by the increasing speed with which new ideas are presented by a rising number of research institutes and private companies throughout the world (Wolfs et al. 2018). High-performance construction materials are preferred because the printing process involves a continuous, high level of material control throughout printing (Lim et al. 2011). Traditional concrete cannot work without formwork, however, with 3DP, no formwork is needed (Paul et al. 2018). To ensure there is no distortion in the bedding layers, researchers recommend using either low viscosity concrete—which is applied to improve the pumping process and requires inserting a chemical accelerator on the nozzle for fast hardening once printed—or low to zero slump concrete (Paul et al. 2018).

3DP relies on a concrete mixed design that is both practical and durable (Huthman and Ibrahim 2017). The design of the mix is considered the most important characteristic of the structural performance and the process of 3D printing (Shakor et al. 2019; Ngo et al. 2018). Extra or alternative additives, cementitious materials, admixtures and aggregates are being employed to accomplish specific properties, for example, ductility, high strength, self-compaction and low CO_2 footprint. 3DP is a mix of water, sand, silica fume, superplasticiser, fibre, fly ash, and cement (Le et al. 2012; Anell 2015; Agustí-juan et al. 2017; Nerella and Mechtcherine 2019). Moreover, previous studies have investigated the different mixes and materials ratios of 3D printing concrete. Agustí-juan et al. (2017) suggested using 20% cement, 1.8% silica fume, 70.5% sand/aggregates, 7% water and 0.2% superplasticiser. Le et al. (2012) conducted a thorough testing of various 3D printed mixes to identify which had the best usability and workability. Finally, the researchers recommended using mix number four, which is 25% cement, 7.1% fly-ash, 3.8% silica fume, 53.5% sand/aggregates, 10% water, 0.7% superplasticiser and 0.05% fibre.

Nerella and Mechtcherine (2016) proposed using 19.5% cement, 7.7% fly-ash, 8.1% silica fume, 56.1% sand/aggregates, 8.1% water and 0.5% superplasticiser, while Anell (2015) recommended using 30% cement, 4% fly-ash, 4% silica fume, 52% sand/aggregates, 10% water, 0.5% superplasticiser and 0.05% fibre. Another study by Malaeb et al. (2015) has tried different mix properties: cement 125 g, sand 80 g, fine aggregate 160 gr, w/c ratio 0.48, superplasticiser 0 ml, flowability rate 0 cm/sec, retarder 1 ml and accelerator 0.5 ml. Furthermore, Different mixes and ratios resulted in different final shapes of the structure and different outcomes. The chosen mix will be described in the methodology chapter, Section 3.3.1.

2.5.8. Economic Aspect of 3D Printing Technology in Construction

The built environment is an important strategic area for any economy. The construction and engineering business is a cornerstone of the worldwide economy, accounting for roughly $10 trillion in yearly sales, or around 6% of the global GDP (Philipp et al. 2016). In 2018, global construction investment was $11.4 trillion, and by 2025, this figure is predicted to rise to $14 trillion (Statista 2020). In the construction sector, labour is essential. Moreover, about 8.4% of the global workforce is produced by the construction sector (ILO 2020). In contrast, the construction sector has struggled towards improve productivity for decades because it is heavily dependent on human labour force, along with little usage of industrialisation or technology (García de Soto et al. 2018). These labour forces account for at least 25% of the overall project cost. Construction progress is frequently hampered by the shortage and/or unskilled labour (Jang et al. 2011).

Over the course of their lifespan, infrastructure and buildings use resources and generate waste (Han et al. 2021). the construction industry is associated with lower labour productivity and higher cost, when comparing it with other manufacturing processes. Furthermore, the construction industry is a capital demanding labour industry (Weng et al. 2020). The productivity of a labour is defined as the amount of output generated per worker per hour (Rojas and Aramvareekul 2003). Labour productivity is impacted by various factors, for instance, the availability of supervisors, the skill level of the labour force (Rojas and Aramvareekul 2003; Abdul Kadir et al. 2005). However, the high cost of the construction industry can be affected by various factors such as, material usage, equipment expense, and labour costs (Weng et al. 2020). The construction sector is struggling with improving its existing state and increasing its overall production (García de Soto et al. 2018). As a result, they are always looking for new methods to improve productivity while cutting expenses (Maskuriy et al. 2019). One way of doing this is by learning and adopting the latest technologies in the sector (Filipe et al. 2017).

Baumers et al. (2016) attribute that technical uncertainty plays a crucial role in forming new sectors, which is especially true for industries based on technology innovations. In order to make business decisions and build a competitive advantage in such emerging sectors, it is necessary to have a comprehensive understanding of the impact of additional technical advancement in these industries (Walsh 2004). Additionally, Schnaars (1989) mentions that technological predictions are "one of the most difficult kinds of forecast to make accurately. There are so many unknowns, and so many possible outcomes, that errors appear everywhere". 3D printing technology has evolved in parallel with the fast progress of computer control systems since the mid-1980s (Han et al. 2021). 3D printing technology was first seen as an essential new industrial manufacturing technique in the third industrial revolution (Han et al. 2021). It has caught the interest of the construction industry due to its potential to reduce the overall greenhouse gas emissions, labour costs and resource needs (Niaki et al. 2019). The worldwide 3D printing industry is expected to grow by 21% in 2020 compared to 2019, with a value of $12.6 billion (Everett 2021). Indeed, increasing the use of new technologies, such as 3D printing technology, will certainly decrease the reliance on human resources, potentially raising productivity and improving worker safety by minimising dangerous tasks (Cai et al. 2019). Therefore, the extensive use of 3D printing technology in construction might be beneficial to the industry while also posing the probability of significant employment losses worldwide. Also, this is an uncertain scenario that requires to be explored more (Hossain et al. 2020).

In recent years, studies have been done to assess the economic impact of 3D printing technology on construction. García de Soto et al. (2018) investigated the impact of digital fabrication (DFAB) on productivity by examining the time and cost necessary to create a robotically-fabricated complicated concrete wall onsite. Data was gathered from several sources, including interviews with specialist contractors working on the DFAB HOUSE, after the different tasks for the traditional and robotically manufactured concrete wall were defined. When there was a lack of information, acceptable assumptions were made. In certain situations, production rates, for example, production and hours of daily output, were collected from RSMeans and verified by the NCCR Digital Fabrication team. Following data collection, a CYCLONE simulation methodology was employed to compare the traditional and robotic building processes quantitatively. The analysis outlined the time and cost distributions for several building scenarios. It was shown that when the robotic building approach is used for complex walls, productivity increases, showing that using 3D printing technology to construct complex structures might yield considerable economic benefits.

The researchers also stated that when considering more practical applications, such as building many structures rather than just one wall, the robot system cost will be more competitive owing to economies of scale, making robotic manufacturing economically viable. Another crucial factor to consider is the robot's limitations. It might be claimed that construction robots might operate for 24 hours straight if the requisite materials are always available. This would without a doubt lead to increased output by the robots. Because the robot requires manual assistance in the case provided in this study, and the issue of several shifts for construction labourers has not been explored, the robot's working capacity is restricted by the robot-human interaction.

Another study was conducted by Weng et al. (2020) to compare productivity and economic cost related to the manufacturing of a prefabricated bathroom unit (PBU, W: 1500 mm; L: 1620 mm; H: 2800 mm) using the precast technique and 3D concrete printing (3DCP). The extent of this study involves electricity expenditure, installation cycle, material consumption and labour cost/ productivity. This study shows that 3DCP-fabricated PBU saves 25.4% in the total cost and 87.1% in energy use. Also, 3DCP had higher productivity with a 48.1% improvement and a reduced self-weight, that is, 26.2% lighter than precast. The formwork-free manufacturing in 3DCP was shown to be responsible for the enhancements. Finally, sensitivity analysis indicates the effect of formwork reuse on the results and the possibility of 3DCP for small batches or custom manufacturing of PBUs. This study calculated the pricing of purchasing a 3D printing machine and concrete batching plant to the equipment cost, which could affect the study results. This is because this machinery could be used multiple times after the project.

Han et al. (2021) also performed research to assess the economic advantage of 3D printing technology when compared to traditional cast-in-situ. It was discovered that 3D printing technology provides substantial benefits over traditional cast-in-situ concrete production since it eliminates the high expense of formwork and manpower. This advantage is magnified in geometrically irregular constructions. Also, it was discovered that the cost of buildings constructed with recycled concrete reduced as the amount of recycled aggregate improved. This was due to the high cost of natural aggregate.

2.5.9. Pros and Cons of 3D Printing Technology

Researchers have dedicated their work to developing this technology and obtaining as many benefits as they can, since the introduction of 3D printing technology in construction (Geneidy et al. 2019). There is an ongoing debate regarding the pros and cons of using 3D printing technology on society and the economy. Wu et al. (2016); Hager et al. (2016); Geneidy et al. (2019); Zhang and Khoshnevis (2013); Chen and Yossef (2015); Pirjan and Petrosanu (2013); Nadal et al. (2017) and Paul et al. (2018) have defined the following pros and cons:

- Pros:

- The ability to print complex objects and shapes for buildings with different materials and in better quality compared to current technologies.
- The high strength in some of the materials that are used in 3D printing compared to current technologies.
- The possibility of personalised customisation for mass production rather than unified stock for the whole mark.
- 3D printing technology has the ability to save time more than the current technology due to the continuously and nonstop work of the printer, except for the maintenance and cleaning of the printer.

- In the production process, the generated waste in 3D printing technology construction methods is less than conventional construction methods. In 3D printing technology process, the nozzle is guided along an established path, at which point the fresh concrete is extruded. This process is done without the need of formwork. So, if there is any waste it will be only from the concrete mix. On the other hand, the waste generated from conventional construction comes from the use of formwork such as plywood, concrete, and steel. Furthermore, the reduction of material waste in 3D printing technology construction methods helps solving issues such as materials waste, energy consumption, environment impact, and the amount of saving on cost and time.
- In the construction industry, one of the major issues on the construction sites is the safety of labourers. The safety factors in 3D printing technology are lower than in current technologies, this is because current technologies require more people working onsite with more supervision, while in 3D printing, which is machine-based technology, the construction process can be fully automated with lesser labour and supervision.

- Cons:

- Some components, such as the cantilever, are still difficult to create using 3D printing technology, which is one of its major limitations.
- As 3D printing technology is a computer-controlled technique, there is a concern that the 3D printing technology could lead to many workers losing their jobs.
- 3D printing technology itself costs more than the current construction technology, including the high cost of the printing device and the materials used in construction.
- There is a concern regarding the mixture of the material content and its workability, buildability and fluidity.
- By applying 3D printing technology, there is a need to have new building codes to ensure that 3D printing technologies are working within the performance criteria and boundaries. For example, the ability of a 3D printing structure on handling wind, earthquakes, thermal performance, etc., and satisfying the performance requirements, for example, toxicity, smoke and fire.

2.6. Technology Adopting Acceptance and Innovation Theories Used to Study the Adoption and Use of 3D Printing Technology

Technology was described as the spoken term for physical labour or skill in ancient times (Samaradiwakara 2014). The term technology was first used in the United States in 1816 in an "application of the Sciences to the Useful Arts" course at Harvard University (Meier 1957). The Encyclopaedia Americana, published in 1832, described technology as procedures, principles and nomenclatures (Samaradiwakara 2014). Furthermore, according to Carr (1999), technology adoption is the "stage of selecting a technology for use by an individual or an organization". With expanding technological requirements in the 1970s and an increase in system adoption failures inside businesses, several academics were interested in predicting system usage (Burns and Wholey 1993). It is essential to consider that customer confidence and approval are important for any new technology's development (Taherdoost 2018). Users' resistance to accepting a new technological system is a regular difficulty that managers face (Lee et al. 2010). Besides, user engagement in system development has always been seen as a factor in system acceptance. (Taherdoost 2018). In general, acceptance is described as "an antagonism to the term refusal and means the positive decision to use an innovation" (Simon 2001). Also, users' acceptance was described by Dillon and Morris (2001) as "the demonstrable willingness within users' group to employ information technology for the tasks it is designed to support."

Many investments have been spent on introducing new technologies by governments and organisations that could change how people live their lives (Rajesh and Rajhans 2014). However, if the improvements are not embraced by the target users, these investments may be in waste (Rajesh and Rajhans 2014). In order for a system to be successful, it must take into consideration the factors that influence the user's decision to use it. (Mathieson 1991). New technology adoption is a common topic of discussion among academics and practitioners. (Taherdoost 2018). By providing an answer, one might be able to develop, analyse, and predict user responses to new technologies more successfully. (Dillon and Morris 1996).

Rogers (1983) defines innovation as a new concept, activity or thing recognised as novel by a person or another adoption unit. The decision to adopt, being persuaded or knowledge of a product are all examples of newness in innovation (Taib 2020). Over the last two decades, researchers have worked to improve our knowledge of the innovation adoption procedure (Taib 2020). Neuman's (2006) theory allows one to visualise complicated social facts and explain why they happen. Theories and models were developed to examine users' acceptance of new technologies through the years.

Furthermore, such theories and models have been proposed in predicting the complexities of human behaviour in terms of adoption patterns and the usage of new technology (Alomary and Woollard 2015). Theories such as the Theory of Reasoned Action, Diffusion of Innovations theory, Theory of Planned Behaviour, Motivational Model, Technology Acceptance Model, Use of Technology and Social Cognitive Theory and Unified Theory of Acceptance were developed to assess individuals' level of satisfaction and acceptance with any technology, but from different perspectives depending on the constructs or determinants that represent there struct (Taherdoost 2018). These theories are also frequently used to explore aspects influencing the customers' behavioural intentions about innovation adoption (Yu 2012).

Although there is more than one theory for technology adoption, this research will identify the theories used to study the adoption of 3D printing technology. These theories are the Theory of Planned Behaviour (TPB), Technology Acceptance Model (TAM), Unified Theory of Acceptance and Use of Technology (UTAUT) and Diffusion of Innovations Theory (DOI).

- Theory of Planned Behaviour (TPB)

Ajzen established the Theory of Planned Behaviours, generally known as TPB (Ajzen 2011). TPB was developed in the field of psychology and is used to describe user behaviour (Aldhaban 2016). TPB is an expansion of the Reasoned Action Theory (TRA) (Ajzen 1985). TRA is a social psychology model that predicts actual behaviour based on subjective norms and behavioural beliefs (Benham and Raymond 1996). Moreover, TRA is considered to be among of the earliest theories to describe users' acceptance behaviour (Hameed et al. 2012). TRA was established by Ajzen and Fishbein (1980) in 1980. In TRA, the way people act may affect how likely they are to use a specific technology based on their mindset and subjective standards of utilising it (Hameed et al. 2012; Ajzen and Fishbein 1980). TPB is regulated by three key elements, two of which were adopted from TRA's **attitude toward behaviour** and **subjective norm**, and the third new one is **perceived behavioural control** (Figure 2-33). (Momani and Jamous 2017). TPB has been one of the most commonly referenced and effective models for predicting the social behaviour of humans since its debut 26 years ago (Ajzen 1985). TPB has been used to study individual approval for the use of a variety of technologies with great success (Momani and Jamous 2017).

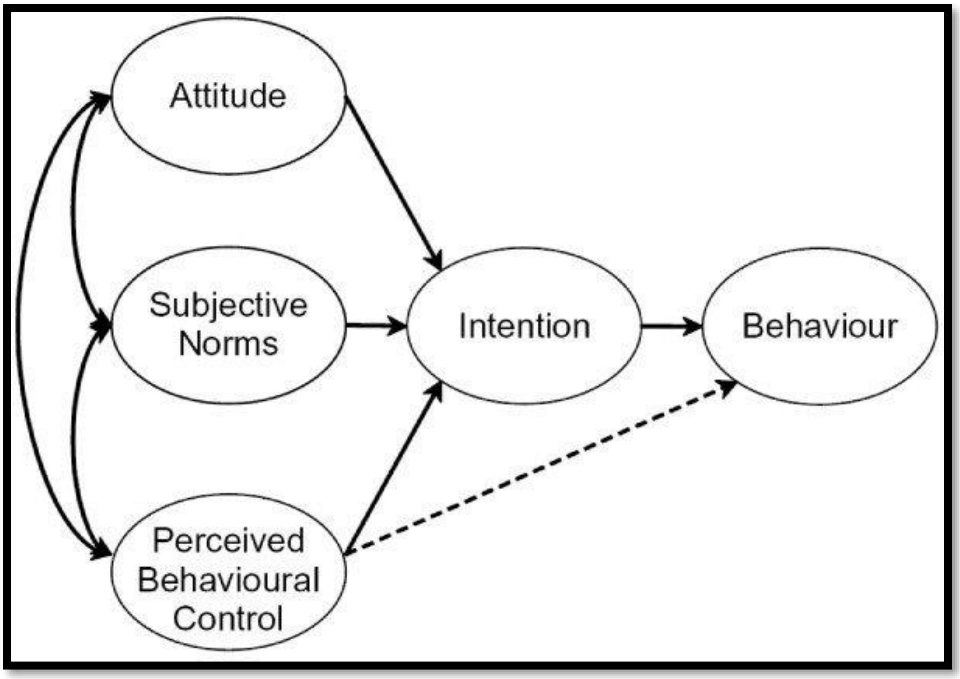


Figure 2-33 Theory of Planned Behaviour (Ajzen 1991).

- Technology Acceptance Model (TAM)

Technology Acceptance Model (TAM) was established by Davis the in 1989 (Davis et al. 1989). The TAM model is the commonly applied and referenced theoretical model, and it is pretty popular among scholars (Heshan and Ping 2004; Lee et al.

2003). TAM was established in the area of Information Technology, but TPB and TRA were established in the field of psychology, making it less general than TPB and TRA (Davis et al. 1989). Moreover, TAM is an extension of TRA (Davis et al. 1989). As shown in (Figure 2-34), the TAM model includes two variables: **perceived ease of use (PEU)**, which is identified as "*the degree to which an individual perceives that using a particular system would be effortless",* and **perceived usefulness**, which is defined as "*the extent to which an individual perceives a positive impact of using a particular system would improve the user job performance."* (Davis et al. 1989). These variables can largely explain and predict consumers' attitudes and behaviours regarding new technology acceptance (Huang et al. 2009). However, the TAM model can only account for around 40% of variances in technological adoption (Venkatesh et al. 2003). Scholars have also identified several flaws in the TAM model, emphasising the necessity to expand the model with new variables, particularly those relating to social and human factors (Legris et al. 2003).

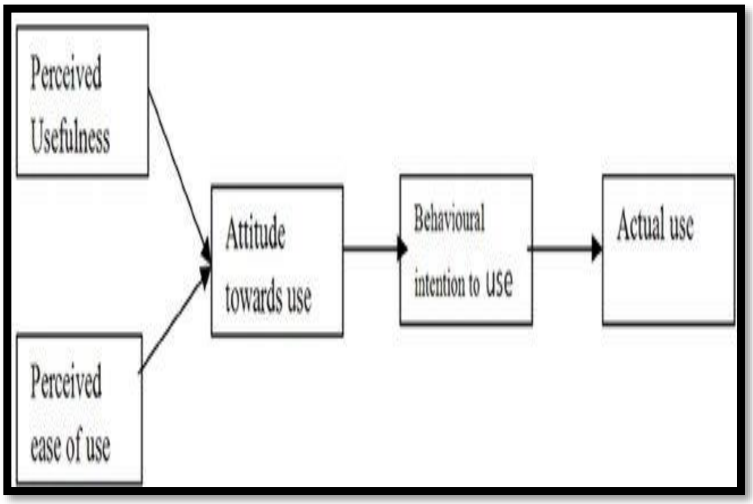


Figure 2-34 Technology Acceptance Model TAM (Davis 1989).

- Unified Theory of Acceptance and Use of Technology (UTAUT)

The Unified Theory of Acceptance and Use of Technology (UTAUT) is a technological innovation theory formed to clarify the intentions and behaviours of using Information Technology (Venkatesh et al. 2003). This theory was introduced by Venkatesh in 2003 to examine and describe "User acceptance of information technology: Toward a unified view" (Venkatesh et al. 2003). It is more thorough in understanding technological success and acceptance drivers (Lu et al. 2005). Furthermore, UTAUT was developed by comparing the differences and similarities between the eight models that were previously employed in the area of information systems, which all got their roots in psychology, communications, and sociology (Taherdoost 2018). These models are Technology Acceptance Model, Diffusion of Innovation, Theory of Reasoned Action, Motivational Model, Social Cognitive Theory, Model of PC Utilization, and Theory of Planned Behaviour (Taherdoost 2018).

The UTAUT theory has four primary constructs: **performance expectancy**, which is the technology's ability to deliver on the expectations of the user by providing benefits and improving performance; **Effort expectancy,** which is the user's perception of the technology's ease of use; **Social influence,** which describes others' predicted result on the user's choice to begin and continue utilising technology; and **Facilitating conditions,** which represent the predictable level of technical and organisational infrastructure required to enable the usage of technology (Venkatesh et al. 2003). These constructs directly influence the user behaviour and intention of using the technology (Venkatesh et al. 2003). Age, gender, the voluntariness of use, and experience are expected to have a slight influence on the impact of the primary concepts on usage behaviour and intention (Venkatesh et al. 2003) (Figure 2-35).

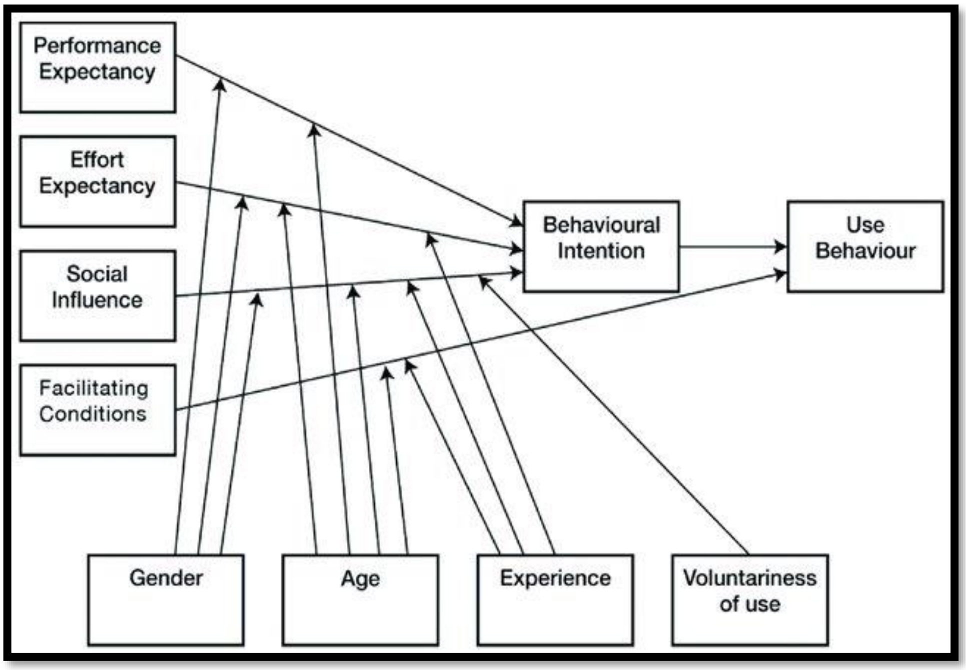


Figure 2-35 Unified Theory of Acceptance and Use of Technology.

- Diffusion of Innovations Theory (DOI)

Rogers proposed the Diffusion of Innovations (DOI) in 1983 (Rogers 1983). DOI is one of the first social science theories for studying any form of innovation. Several diffusion experiments conducted in the 1950s led to the development of this theory, which focused on individual variations in innovativeness (Rogers 1983). Moreover, the DOI model combines three important elements: adopter characteristics, innovation characteristics and the innovation-decision process. In innovation-decision, there are five phases: Knowledge, Persuasion, Decision, Implementation and Confirmation (Rogers 1983). In innovation characteristics, there are five characteristics: Complexity (COMX), **Relative Advantage (RADV)**, **Trialability (TRB)**, **Observability (OBS)**, and **Compatibility (COMP)** (Rogers 1983) (Figure 2-36). Finally, in adopter characteristics, there are also five main groups: early adopters, early majority, late majority, and laggards (Rogers 1983). DOI is a useful model for studying technology implementation, adoption, and evaluation (Taherdoost 2018). This is because DOI focuses more on organisational factors, best practice factors and environmental factors (Ungan 2004).

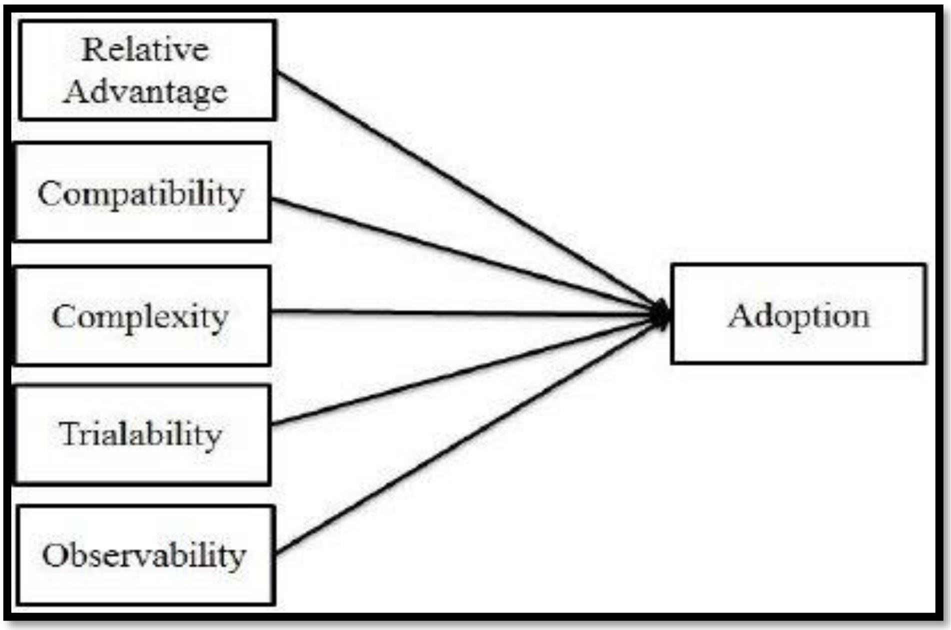


Figure 2-36 Diffusion of Innovations Theory (Rogers 1983).

2.6.1. Research Related to the Adoption and Use of 3D printing technology

Oettmeier and Hofmann (2017) studied the adoption of additive manufacturing technologies for the production of industrial parts in Switzerland. This study applied the Diffusion of Innovations Theory (IDT) and Technology Acceptance Model (TAM) to investigate the adoption. This research model included four factors: technology-related factors, firm-related factors, market structure-related factors and supply chain-related factors. An online survey was sent to 195 firms. The targeted group for this study were the executive managers in the field of production, logistics, and supply chain management. The results indicated that compatibility and demand-side benefits are the main determinants of the adoption of additive manufacturing. Furthermore, it has been suggested that all inter-organisational factors should be considered when investigating the possibilities of the adoption of technological innovation.

Chatzoglou and Michailidou (2019) applied the Technology Acceptance Model (TAM), Diffusion of Innovations Theory (IDT) and Theory of Planned Behaviour (TPB) in order to examine people's intentions toward using 3D printing technology in their workplace. The study took place in several European countries (mostly in Finland, UK, Greece and Germany). An online survey was conducted through social media using the non-probability convenience and snowball sampling techniques. Furthermore, there were 258 valid responses. This study's findings emphasised that to understand the respondents' intention of using 3D printing technology, compatibility, attitude, output usability and perceived usefulness are essential attributes. The limitations of this study are that the sample size is quite small due to the sample method. Since the sample came from more than one European country, there are differences in the readiness levels in each country to accept the new technology.

Schniederjans (2017) combined the Diffusion of Innovations Theory (DOI) and Unified Theory of Acceptance and Use of Technology (UTAUT) to explore the adoption of 3D printing technology in the manufacturing sector in the United States of America (USA). The study was concentrating on top management representatives from manufacturing firms across the USA. An online survey was sent to 270 top management representatives in different firms. The results of this study revealed that the category of top management has an impact on the adoption speed by the firm, but it doesn’t substantially impact the actual speed.

Furthermore, complexity and effort expectancy were found to offer conflicting evidence on the role of the willingness to adopt 3D printing. Some of the limitations in this study are that the usage of the phrase additive manufacturing, as compared to 3D printing, is up for discussion because of the other research concerning the differences and similarities among the two phrases. This study only focused on some of the broader usage of 3D printing, and not the various technologies that are being used in manufacturing. Moreover, there was an issue with the method of sampling, where some large organisations had more resources to adopt the technology as compared to the relatively smaller organisations. The author made more than one recommendation in this study, which is that, in future research, small organisations should be studied to assess the adoption of 3D printing. Also, future studies must concentrate on the advantages of using 3D printing in mass production lines, as well as in industries such as the aeronautical industry and medical industries.

Marak et al. (2019), aimed to assess the adoption of 3D printing technology in selected industries in India. For this study, the Diffusion of Innovations Theory (IDT) was used as a theoretical model. Also, a section was added to demonstrate the challenges that would be faced in the adoption of 3D printing technology in India. An online survey was sent out to companies from service sectors as well as manufacturing sectors in India. The online questionnaire was sent to 400 firms and there were 92 respondents. The findings of this study imply that there was a significant correlation between the adoption and the relative advantages, complexities and trialability. Simultaneously, compatibility and observability appeared to have a non-significant association with the adoption. Furthermore, the understanding of significant financial, infrastructural, and human resources challenges could help the process of adopting 3D printing technology for both suppliers and manufacturers.

Wu et al. (2018) attempted to propose a conceptual framework to help with the adoption of 3D printing technology in the Australian construction industry. After going through the literature review, it was discovered that 14 factors influence the adoption of 3D printing technology. These 14 factors were distributed under four sections: 1 - Technological readiness, 2 - Effectiveness of 3D printing, 3 - Organisational support and 4 - Policy and regulatory consideration. Further, the factors under each section are potential reduction in construction time, building codes and regulations, potential reduction in life cycle cost, successful cases, readiness of concrete printing technology, project quality assurance, top management commitment, capability of being modified and demolished, the readiness of steel printing technology, liability for 3D printed components, technology integration, standard implementation, better environmental performance, and availability of resources

Moreover, five senior managers who are working in Western Australia helped to finalise these factors, as well as their categorisation. The study was limited to the construction industry's professionals such as project management, site employees, senior management, clients, consultants, architectural designers, main contractors, and subcontractors/suppliers. The sample size for this study was a non-probability sample, the participants selection was based on their willingness to take part in the study, and not on the whole population. An online survey was sent through email and Linkedin, and there was a total of 105 complete responses. Also, the results of this study revealed that liability for 3D printed components, top management commitment, and building codes and regulations are the most important factors affecting adoption, arguing that the soft parts of adopting 3D printing need to compete with the technological advances. This is the first study that presents a conceptual framework for the adoption of 3D printing technology in the construction industry. This research recommends future studies to examine what skills and technical knowledge are required from project managers in order to adopt 3D printing technology in the construction industry. Studies also need to be conducted to figure out how to develop strategies to match the building codes and the 3D printing technology's standards. Finally, a framework to combine the differences between the manufacturing industry and the construction industry must be developed.

Olsson et al. (2019) analysed the introduction of 3D printing of concrete in the construction industry. An online survey was sent to Norwegian companies that were engaged in construction management consulting, engineering, and architecture, or were suppliers of pre-assembled modules, building owners and clients. A total of 235 persons were received, of which only 36 were valid. The findings imply that the primary enablers of innovation are collaborations with partners, industry-academia collaborations, and effective leadership. Additionally, one of the limitations of this study is that it is hard to obtain representative samples. Also, future studies are needed to shape the expectations for the development of technology within the construction sector.

Kianian et al. (2016) investigated the adoption of different types of additive manufacturing (AM) such as production, Rapid Prototyping (RP) and 3D printing technologies in Sweden. The authors investigated two main questions; 1 - What are the existing applications of AM in Sweden? and, 2 - Among the users, what are the aspects that can explain the variation of AM adoption? The data for this study came from a survey that was done between 2013 and 2014 by 3dp.se and had a response from 55 Swedish AM users from different universities, companies, and research institutes. Also, 15 additional responses were added by the authors, which have not been considered in the survey. The main findings of this study are that the users display variation amongst AM applications and are expanding it more than just rapid prototyping. Being a small-sized company and using multiple AM technologies are considered to be the two positive factors that can incorporate management and production and affect the decisions of firms to expand classical rapid prototyping.

Geneidy and Ismaeel (2018) investigated the potential of applying 3D printing technology for buildings in Egypt. This research used a mixed-method approach where they interviewed 15 partitioners of different backgrounds such as engineering construction, design and planning, management and consultancy and research and development. Furthermore, this interview helped in the design of an online questionnaire that received 15 full responses. The results illustrate that the main factors delaying the wide use of technology are time, awareness, and cost.

Wang et al. (2016) explored the adoption of 3D printing systems in small scale manufacturing in-home settings amongst Chinese customers. The Diffusion of Innovations Theory (IDT) and Technology Acceptance Model (TAM) were applied in this research to significant aspects that affect the decision of individuals to adopt 3D printing systems. A survey was sent to 281 individuals from various disciplines such as design academia, graphic designer, interior design, fashion design and advertising design. Moreover, from 281 participants, 256 were considered valid. The findings demonstrate that the early adoption of 3D printing systems will be from younger people. Also, it was found that females find these systems easier to use as compared to males. On the other hand, males tend to be more affected by their perception of satisfaction of employing these systems. Additionally, highly educated professionals and designers are more possible to adopt 3D printing systems than others. The study makes a recommendation for future studies to examine the effectiveness of 3D design tools to inspire a mini-revolution in designs driven by the massive consumer base in China.

Calli and Calli (2020) studied the intention of using 3D printers, taking into account the ownership status. This research used a mixed-method research approach to study the owner and the non-owners. The sample size of the participants are academicians who were interested in exploring the behaviour on the adoption of new technologies, service providers, 3D printing experts, and participants working in consumer marketing, participated in the focus group study that was aimed at enhancing the outcomes from the systematic review, improving context-specific factors, and exploring new ideas. Furthermore, a model combining the ease of use, perceived usefulness, personal innovativeness, change readiness and enjoyment was tested on a sample of 416 participants from Turkey. The results of the owners revealed that all factors have a significant effect on the intention for owners to use 3D printers, except for the factor of perceived usefulness. On the other hand, personal innovativeness did not show a significant impact on the intention of owners to use 3D printers. Additionally, the limitations of this study were that there was an issue in the sample technique method where it was difficult to reach the whole population.

2.7. Sustainability Development

Both "Sustainability" and "Sustainable Development (SD)" have been regularly misinterpreted, and they are occasionally used interchangeably (Ainger and Fenner 2014; Gilmour et al. 2011). Sustainability indicates the capability to sustain a 'desired state' for a long period of time, whereas Sustainable Development is seen as the instrument necessary to reach the required 'Sustainability' (Waas et al. 2011). Moreover, Sustainable Development may be considered as a method to address unsustainability, whereas the core concept of Sustainability appears to be how to attain long-term Sustainability of living systems (e.g., guidelines for decisions, clear ethical values) (Abubekr 2019). As a result, Sustainable Development must be founded on principles that include all of society's concerns (Waas et al. 2011). Sustainable Development is defined as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Holdgate 1987). This definition was presented by the World Commission on Environment and Development (the Brundtland Commission) and it is believed to be one the most frequently recognised definitions.

The idea of Sustainable Development necessitates viewing the globe as an interconnected system in which any actions performed by one country impact other nations: for instance, the air quality in Asia is impacted by the air pollution from North America (IISD 2018). Another difficulty that must be conquered to achieve sustainable development is limiting the impact of climate change (Rashid 2017). Scientists have determined that climate change must be seen as a severe and plausible possibility and that all economic, social and environmental decisions must take it into account (Holdgate 1987). Sustainability is a way to make sure that future generations will be able to live by keeping the natural and built environments in good shape and making sure that natural resources and people will continue to exist (Yılmaz and Bakış 2015). At the same time, sustainability is a system with several parts that aims to improve the quality of life for everyone by helping those who are struggling in building strong relationships between people by highlighting cooperation and public benefit and changing the way the economy works so that it doesn't depend on natural resources (Vehbi and Hoşkara 2009). The main goal of the concept is to find a balance between place, time, and people. This means that all nations and living things should get an equal share of the world's resources and that we should think about future generations (Yılmaz and Bakış 2015).

The Triple Bottom Line (TBL) model of sustainable development is relied on three factors: the economic, social and environmental factors, which are depicted in (Figure 2-37), (Gupta et al. 2015). TBL promotes a healthy balance of these factors (Selmes 2005). Other methods were developed, such as the Russian Doll Model, proposed by O' Riordan, which states that the economy is presented inside society, and society is presented in the limits of the environment (Figure 2-38) (Jacobs and Cilliers 2017). Also, Mebratu developed the Cosmic Interdependence Model in 1996, which is similar to the Russian Doll model (Figure 3-39). This model indicates that three dimensions are connected due to the interaction of the three dimensions with each other (Jacobs and Cilliers 2017).

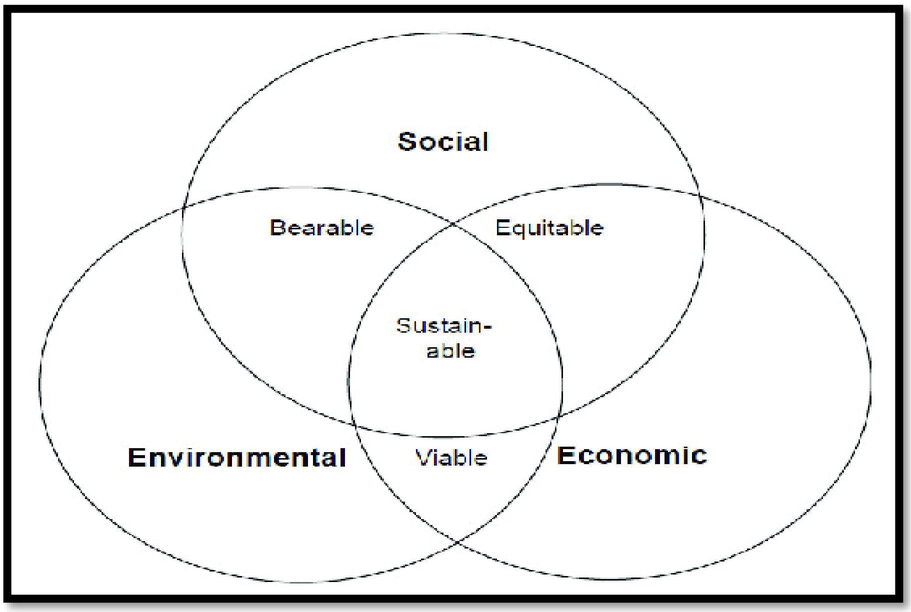


Figure 2-37 Triple Bottom Line (Gupta et al. 2015).

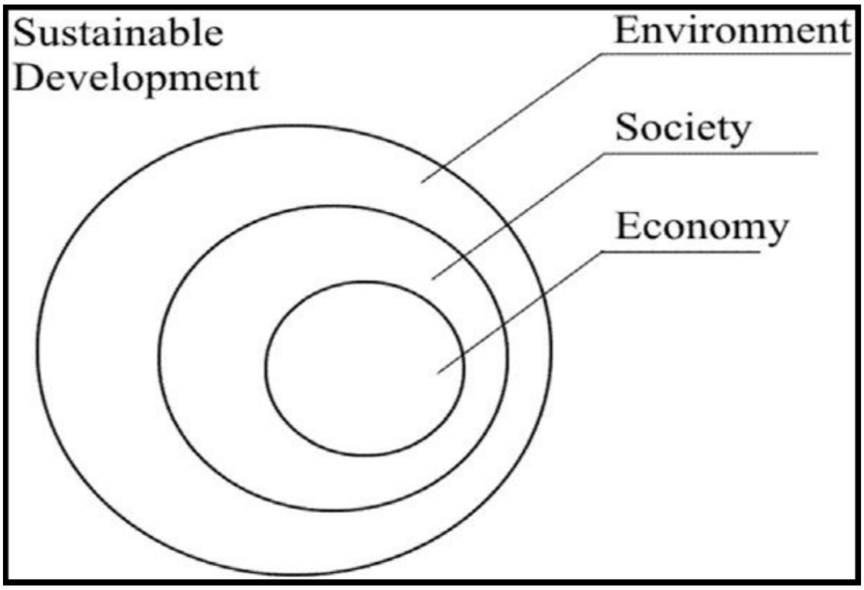


Figure 2-38 The Russian Doll Model (Jacobs and Cilliers 2017).

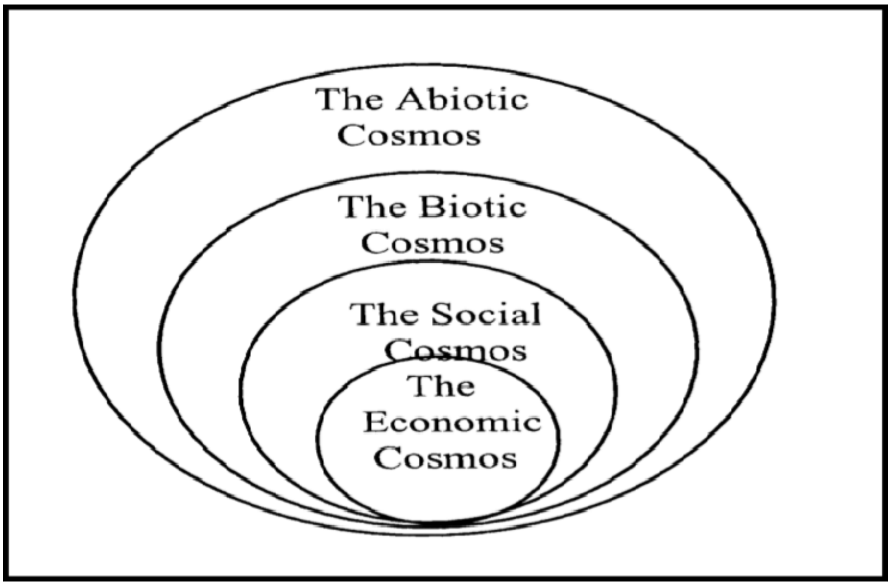


Figure 2-39 The Cosmic Interdependence Model (Jacobs and Cilliers 2017).

2.7.1. Principles of Sustainability

The UN launched several campaigns to promote the sustainable development agenda, including the 1992, Agenda 21 plan of action at the UN Conference on Environment and Development (UNCED) and World Summit on Sustainable Development in Johannesburg, South Africa in 2002, which was attended by more than 178 governments from around the world (Division for Sustainable Development 2006). With eight primary aims, the Millennium Development Goals (MDGs) were introduced in 2002 towards improving the lives of millions of people (United Nations 2015). One of its objectives is to achieve environmental sustainability by requiring all countries to implement sustainable development concepts into their policies and programmes by 2015 (Figure 2-40). (United Nations 2015).

Figure 2-40 Millennium Development Goals (MDGs) (United Nations 2015).

The Sustainable Development Goals (SDGs) was adopted by United Nations adopted on September 25, 2015, which are a continuation and expansion of the previous Millennium Development Goals (MDGs). The latest agenda emphasises a comprehensive strategy based on the principle of "leaving no one behind" in order to achieve Sustainable Development for everyone (SDGs 2015). Throughout its 15-year lifespan, 'Envision2030' encourages the mainstreaming of the establishment of Sustainability with 17 essential principles to alter the world and accomplish the three dimensions of sustainable development (Figure 2-41). (United Nations 2015). Additionally, 175 nations signed the Paris Climate Agreement, on April 22, 2016, pledging to keep global temperature rise well under two degrees Celsius. The Paris Agreement is also a part of the SDGs and provides a plan for reducing emissions and building climate resilience (United Nations 2015).

Figure 2-41 Sustainable Development Goals (SDGs) (United Nations 2015).

2.8. Sustainability in Construction

The idea of sustainability is increasingly being used in construction engineering (Zavadskas et al. 2018). Construction engineering includes all stages of a building's life cycle, including design, project management, maintenance, construction activities, rehabilitation of infrastructure or structure items and construction planning (Zavadskas et al. 2018). It is commonly acknowledged that the construction industry can contribute significantly to the importance of SD in social progress, environmental protection, and increase of economic (Heravi et al. 2015). Furthermore, the term Sustainable Construction (SC) evolved as the idea of SD simultaneously (Kibert 2008). In this setting, the fast progression of scientific and technical advances and people's perceptions of project sustainability are two significant drivers of sustainable building development (Zhang et al. 2014). Taking these factors into account offers new possibilities for modelling various methods of SD (Zhang et al. 2014). There are several initiatives aimed at understanding the principle of sustainability in the built environment, for instance Sustainable Communities (Social Sustainability), Sustainable Architecture (Ecological Architecture) and Sustainable Building (Yılmaz and Bakış 2015).

The most essential goal of Sustainable Development is sustainable communities or social sustainability, which focuses on some basic human rights and freedoms (Yılmaz and Bakış 2015). As a result, there appears to be a substantial body of research supporting the value of construction projects as the beginning of establishing Sustainable Communities. According to Edwards and Turrent (2000), "Living in harmony with the environment has become an essential component of the design of homes and neighbourhoods in the third millennium". The most visible example of fundamental freedom and rights is balance among generations and equality (Yılmaz and Bakış 2015). Resources can be transferred to future generations in order to preserve their existence. Moreover, social sustainability will offer basic needs such as increased life quality, improved health conditions, work, secured right to life for future generations and long-term cultural activities and education for every individual (HKU 2002).

Sustainable Architecture (Ecological Architecture) is described as a design that serves human needs while having a minimum impact on the environment (Edwards and Turrent 2000). It is also defined as a set of actions that take care of ecological balance, limit environmental harm, use materials effectively and use energy and water efficiently during construction (Yılmaz and Bakış 2015). The principles of sustainable architecture can be classified under three titles “Humane Design”, “Economy of Resources, and “Design of Life Cycle” (Kim and Rigdon 1998). First, Humane Design strategies are Design for Human Comfort, Urban Design Site Planning, and Preservation of Natural Conditions; the strategies of Economy of Resources are Material Conservation, Water Conservation, and Energy Conservation; finally, the Design of Life Cycle strategies are Post- Building Phase, Building Phase, and Pre-Building Phase (Kim and Rigdon 1998).

Sustainable building is a term that represents the implementation of sustainability concepts to reduce the environmental effect of construction projects. John et al. (2005) indicated that buildings that have minimal negative effects on the natural and built environment, both concerning buildings themselves, as well as their immediate surrounds and the larger regional and global contexts. As stated by the World Green

Building Council (WGBC), green buildings in the beginning emerged as a reaction to natural resource consumption and excessive; however, since the development of the green building idea, green building construction turned out to be more than energy use efficiency (WGBC 2013). The U.S. Green Building Council (USGBC) defined green buildings as "Green building is a holistic concept that starts with the understanding that the built environment can have profound effects, both positive and negative, on the natural environment, as well as the people who inhabit buildings every day. Green building is an effort to amplify the positive and mitigate the negative of these effects throughout the entire life cycle of a building" (USGBC 2014).

2.9. Impacts of Construction on the Environment

People require a large number of buildings to support their existence during civilisation. During the construction of buildings, operation and maintenance and demolition, buildings generate plenty of environmental issues (Yılmaz and Bakış 2015). Buildings, which consume many natural resources and energy, cause climate change by affecting water and the quality of air in urban areas (Vyas et al. 2014). The building sector is critical to accomplishing the 11th and 15th Sustainable Development Goals. In 2018, the International Energy Agency (2018) announced that, the global energy consumption average growth rate has nearly doubled since 2010. This intense energy requirement boosted CO_2 emissions by 1.7% in 2018, setting a new record. In the same year, the building construction industry and its processes contributed to 36% of the worldwide overall energy usage and 40% of CO_2 emissions (IEA and UNEP 2018).

Shrubsole et al. (2019) asserts that buildings take an essential part in the transition to a low-carbon economy. Moreover, the construction industry is one of the world's most resource-intensive industries (Abubekr 2019). As a result, the effects of building operations on both ecosystems and humans are becoming increasingly severe (Abubekr 2019). These negative effects of the construction industry can be summarised as an increase in global warming, loss of agricultural areas, decrease in biological diversity, depletion of unrenewable resources, soil and water pollution, destruction of forest areas and destruction of natural green areas (Yılmaz and Bakış 2015).

Indeed, the built environment and the performance of buildings necessitate further efforts to include sustainability (Ding 2008). Because the construction and environment activities appear to be strongly linked, the construction sector is viewed as a focus point for environmental challenges (Jain 2013). It is clear that the effects of the construction industry on the surroundings and the work during the lifecycle of the project are mostly permanent (Ding 2008). As indicated in (Figure 2-42), these life cycle stages can be classified as embedded, including extraction, manufacturing, transportation, construction, maintenance, destruction, and disposal, differing on the system boundary or operations, which is associated with the running of the building (TU Delft 2017). Although the construction phases significantly impact the environment, there is a need to assess all phases in the building's life cycle (Ogunmakinde et al. 2017).

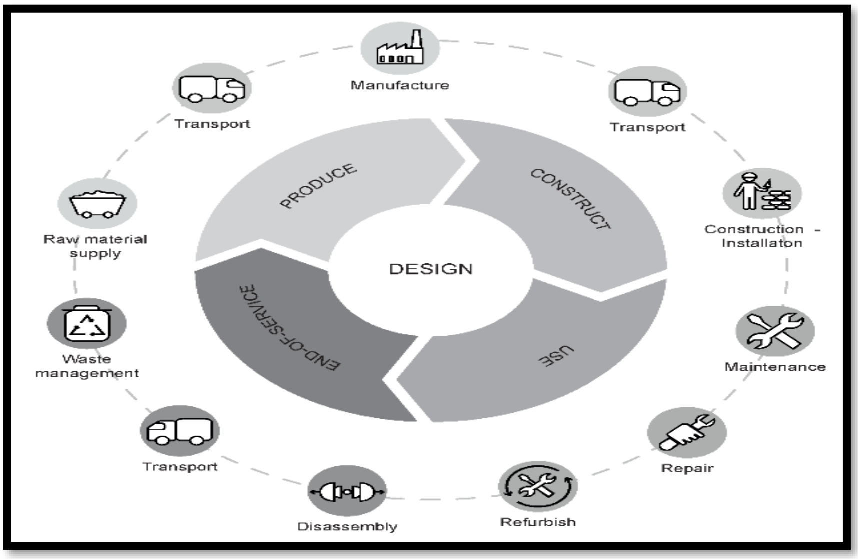


Figure 2-42 Life Cycle of a Building (TU Delft 2017).

2.10. Methods and Tools for Environmental Performance for Buildings

It is difficult to provide the exact meaning of the phrase "building performance" because different participants in the construction industry have different experiences and requirements (Cole 1998). For example, Economic performance focuses on economic success, whilst residents are more concerned with health-related issues (Haapio and Viitaniemi 2008). Concerns about the influence of buildings on the environment have grown during the last several decades (Wong and Kuan 2014). The scientific community has long-established and recognised the link between environmental issues and the building sector (Li et al. 2017). It was necessary to assess the influence of buildings on the environment because of the identified concerns (Li et al. 2017). Throughout the years, there has been an increase in intensity in assessing buildings environmental performance (Wong and Kuan 2014). The application of building performance approaches enables design teams to demonstrate the sustainability factors benefits of the building they create to the community (Li et al. 2017). Therefore, a calcification was done by Bragança et al. (2010) that categories building performance methods for buildings into three categories: Life-cycle assessment (LCA) systems, Sustainable building rating and certification systems and Systems to manage building performance (Performance-Based Design).

- Life-cycle assessment (LCA) systems

Life-cycle assessment (LCA) is a method of evaluation that covers all phases of the life cycle, including raw materials, transportation, manufacturing, operations and end of life (Bragança et al. 2010). It is frequently seen as a complete and systematic method of environmental evaluation, particularly in building evaluation (Cabeza et al. 2014). This type of building evaluation is time-consuming and data-intensive, but it enables a more comprehensive assessment of both operational and embodied energy, as well as GHGE (Bragança et al. 2010). A structure comprises hundreds of thousands of different goods, and a construction project may include tens of businesses. Furthermore, a building's projected life cycle is quite long, and it could be from tens to hundreds of years (Bragança et al. 2010).

- **Sustainable building rating and certification systems**

Sustainable building rating systems help translate a long-term aim into specific objectives (usually in the form of a checklist) for assessing overall performance (Bragança et al. 2010). Various sustainable building ratings and certification processes have different perspectives, yet they all have things in common (Bragança et al. 2010). In general, these methods and techniques address the same areas of life cycle performance and building in a certain way: indoor environment, energy, site, materials, and water (Bragança et al. 2010).

There are three main building certification and rating systems that serve as the foundation for the rest of the world's methods: the Sustainable Building Challenge Framework (SBTool), that has been established through the cooperation of 20 countries (Bragança et al. 2010), the Building Research Establishment Environmental Assessment Method (BREEAM) (Bre 2019) and the Leadership in Energy and Environmental Design (LEED), which was established in the U.S.A. (USGBC 2019).

Almost all rating and certification processes for building sustainability are determined by local legislation or regulations, as well as traditional construction practises (Bragança et al. 2010; Haapio and Viitaniemi 2008). Because the weighting of each category and indicator in the assessment is defined based on economic, environmental, and socio-cultural considerations at the local context. Additionally, most of the techniques proposed thus far can only have local or regional reflexes, which is considered a disadvantage (Bragança et al. 2010; Haapio and Viitaniemi 2008). Nevertheless, some global scale approaches may be used. It is necessary to ensure that one life cycle stage will not have a negative impact on another (Crawford et al. 2010). Another disadvantage is that when applying different weighting criteria to different categories, one criterion will be more important than another, which will lead to different benchmarks and system boundaries (Haapio and Viitaniemi 2008).

- **Systems to manage building performance (Performance-Based Design)**

The term "Performance-Based Building" refers to a method of approaching building-related products, services and processes that focuses on the desired outputs (Bragança et al. 2010). Any design solution that can be proved to achieve the design objectives can be used in this method (Bragança et al. 2010). The performance method can only be used as a whole if more progress is made in the following three main areas:

- The strategies for achieving the required performance.
- The specification of suitable building performance requirements.
- The procedures for determining whether or not the necessary performance has been met.

- **Assessment Tools for Buildings**

Over time, tools have been created to improve energy and reduce GHG emissions by enhancing the building design, including energy efficiency equipment, using recycled building materials, and promoting improved management and site planning (GBI 2013). Even while they are expected to include the whole building, involving energy consumption, most of the tools are made employing a bottom-up method, where the building components and materials are combined together (Erlandsson and Borg 2003). Decision-making tools were also created in line with the standards of Performance-Based Design (mostly in research groups) (Bragança et al. 2010). Examples of the used tolls related to the categories of environmental building performance mentioned methods above are LCA House (Finland), EcoEffect (Sweden), Eco-Quantum (Netherlands), ENVEST (U.K.), LEED in the U.S., ATHENA (Canada), BREEAM in the U.K. and BEES (U.S.) (Figure 2-43) (Bragança et al. 2010; Ding 2014; Doan et al. 2017; Madad et al. 2019). The chosen method or tool for this study is Life cycle assessment (LCA). More details regarding the LCA method will be discussed in-depth in the next chapter. However, the following sections will discuss how LCA is being used in the construction sector in Saudi Arabia and review the previous studies on 3D printing technology and LCA in the construction sector.

Figure 2-43 Green Building Ratings Systems Around the World

2.11. Life Cycle Assessment in Saudi Arabia in the Construction Sector

The LCA methodology was applied in many different fields in the Saudi context. These studies primarily focus on the environmental performance in the electricity sector (Mansouri et al. 2013), air conditioning in residential buildings (Almutairi 2018), marine environment (Taelman et al. 2014), waste to energy (Ouda et al. 2016) and waste management system (Alkhuzai 2014). However, for the construction sector, only one study was done by Asif et al. (2017). An LCA study was conducted on a three-bedroom semi-detached villa in Dhahran, Saudi Arabia. This study aimed to assess the embodied energy and the environmental impacts of 18 primary construction materials in the presented villa. The system boundary of the study was 'cradle-to-gate'.

Additionally, the initial data were gathered from the project file, which included interviews with the construction engineer, contractor, and project director. Data were also collected through the bill of quantity (BOQ) of the project. SimaPro software was used to assess the environmental impacts of the buildings model. The Cumulative Energy Demand method 1.04 and Environmental Product Declaration (EDP) methods were used by the researchers to calculate the embodied energy and the environmental impacts. The results of the study indicate that after the analyses of the materials, concrete had the highest contribution to the environmental impact of the house and had 43% of the total embodied energy. Also, steel showed the second-highest environmental impact and embodied energy material. Asif et al. (2017) claim that this is the first LCA study to be conducted in Saudi Arabia and the Gulf Cooperation Council (GCC) region. After analysing the study, the researcher found that there are some issues with this study. Firstly, the machinery calculations were not calculated (concrete pump and mixer). Another issue was not performing sensitivity analysis to show the enhancement for future research.

2.12. 3D Printing Technology and Life Cycle Assessment Studies in Construction

Previous studies were done to evaluate the environmental performance of digital fabrication methods compared to conventional methods in the past using different types of materials in different fields. Kreiger and Pearce (2013) examined distributed polymer products' environmental and cost benefits using 3D printers and conventional manufacturing. The findings show that distributed manufacturing using 3D printing manufacturing can have a less environmental and financial impact on a range of products than conventional manufacturing. Faludi et al. (2015) examined the environmental effects of a traditional numerical (CNC) milling machines vs two additive manufacturing machines and found out that additive manufacturing machines consume less energy and produce less waste than CNC milling machines. Kafara et al. (2017) did a comparison research of 3D printing technology and traditional manufacturing methods for mould core fabrication in the production of carbon fibre reinforced polymer (CFRP). The findings indicated that 3D printing technology manufacturing was more environmentally friendly than conventional manufacturing. Scholars have begun to investigate 3D printing of earth-based materials in recent years, including cob as an environmentally acceptable alternative to 3D printed concrete (Perrot et al. 2018). The results indicates that the use of 3D printing of earth materials will have a positive impact on the benefits of 3D printing technologies by decreasing carbon footprint, transportation, and waste (Gomaa et al. 2019; Veliz Reyes et al. 2018).

In the Middle East and Saudi Arabia, concrete is the most commonly used materials in construction (GaStat 2019). So, the concentration of this research will be on the studies that used concrete. Agustí-Juan and Habert (2017) proposed environmental principles for digitally produced building design. The important characteristics were collected from the Life Cycle Assessment of three case studies: the wall, the floor, and the roof. The environmental evaluation revealed that the constructions' relative sustainability was mostly dependent on the production of building materials. The influence of digital fabrication techniques, in particular, was minor when compared to the materials production process. The study also emphasised the possibilities for integrating extra functions in structural parts using digital fabrication to lower the total environmental impact of such multi-functional elements. Finally, the research demonstrated the ability of digital manufacturing to minimise the percentage of highly industrialised components used in a project, which also are connected with significant environmental impacts.

Another investigation was conducted by Agustí-juan et al. (2017) to explore the environmental benefits of digital manufacturing techniques, specifically when employed in complex concrete geometries. The study evaluated a wall structure constructed using two different methods: traditional and digital fabrication, in order to evaluate the Life Cycle Assessment of both walls. The 'cradle-to-gate' system boundaries for this investigation included raw material extraction, transportation, building materials, digital technology manufacture and robotic fabrication. The functional unit for this study was 1 m^2. Furthermore, to demonstrate the different degrees of complexity, LCA was applied to various forms of walls, single-curved, straight, and double-curved walls. The study used the SimaPro 8 software and Recipe Midpoint (H) v1.12 as an assessment method. The study results show that the environmental benefits of applying digital fabrication to complex structures are better than conventional construction. Also, the results demonstrate that increased complexity may be obtained through digital manufacturing without facing higher environmental costs.

Kuzmenko et al. (2020) conducted a Life Cycle Assessment study on a generic building system (wall) redesigned for 3D concrete printing. The system boundary for this study was cradle-to-gate, and the functional unit was 1 m^2. Furthermore, the study used the Recipe Midpoint (H) method as a life cycle impact assessment (LCIA). The results reveal that the impact of the 3D printing robot on the total results is indeed significant, and in some categories, it had more impact than the materials. A sensitivity analysis was done to improve the robotic system and concluded that the environmental impact of manufactured items might be enhanced by 15% by improving the efficacy of industrial 3D printing robotics.

Weng et al. (2020) compared the environmental impacts of manufacturing a prefabricated bathroom unit (PBU, W: 1500 mm; L: 1620 mm; H: 2800 mm) using the precast technique and 3D concrete printing (3DCP). The extent of this study involves electricity expenditure, installation cycle, material consumption and labour cost/productivity. This study shows that 3DCP-fabricated PBU reduces CO_2 emissions by 85.9%. Han et al. (2021) used life-cycle assessment techniques to estimate the environmental effects of 3D printed structures built of recycled concrete. To further estimate the sustainability possibility of recycled concrete utilised in 3D printed buildings, an LCA framework was defined based on the properties of concrete 3D printing. The researchers discovered that, while increasing the use of recycled aggregate may result in lower harmful emissions, the environmental effect of 3D printing concrete production is often more significant than that of a traditional cast-in-situ concrete building. This is because the 3D printing process requires more cement to achieve consistent concrete performance.

Mohammad et al. (2020) used LCA to explore the environmental performance of3D concrete printing (3DCP) vs conventional construction by studying the case scenarios of four walls (3DCP with reinforcement concrete, conventional concrete construction, 3DCP without any reinforcement and 3DCP without any reinforcement and using a lightweight printable concrete material). The system boundary for this study was 'cradle-to-gate'. In all four scenarios, a 1 m^2 external load-bearing wall was used as a functional unit. The study applied the TRACI midpoint method as a Life

Cycle Impact Assessment. The study results concluded that 3DCP has a significant positive impact on the environment compared with conventional construction. These environmental benefits, however, were lessened when 3DCP was combined with the usage of traditional reinforcing components. Furthermore, the study used different concrete mixtures with 3DCP and revealed that when changing the mixtures, further decrease will be observed in the Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP) and Fossil Fuel Depletion (FFD).

2.13. Research Gap and Future Directions

After reviewing the literature regarding the adoption of 3D printing technology as a new construction method in Saudi Arabia from different aspects, it was found that 3D printing technology is a promising technology to be adopted in the construction industry in Saudi Arabia. The literature also discovered that Saudi Arabia has issues regarding the housing sector, such as the lack of using modern methods. Therefore, Saudi Arabia introduced a new vision, "Saudi Vision 2030" to overcome these issues. Life Cycle Assessment (LCA) is considered to be a new tool to be used in the construction sector in Saudi Arabia. Asif et al. (2017) made an LCA study for a conventional three-bedroom villa in Saudi Arabia and claimed that this study is the first LCA study to be done not only in Saudi Arabia but in the Gulf Cooperation Council (GCC) area. Regarding applying the Life Cycle Assessment (LCA) method and the economic aspect, the previous studies comparing 3D printing technology and conventional construction methods were done on small scales (one building component). The previous studies on the adoption of 3D printing technology in construction were done on top management, manufacturing companies, the construction industry, in general, executive managers in logistics and academicians in different fields and countries around the world. The literature also revealed that there wasn't a specific study directed to Architects and Civil Engineers, even though they are the ones who use this technology the most in the construction sector. Other stakeholders such as executive managers and top management usually focus only on the cost and time aspects of the technology.

The review of the previous studies regarding Life Cycle Assessment (LCA) and the economic, and professional aspects of 3D printing technology in construction has revealed a gap that needs to be filled concerning the use of LCA in Saudi Arabia, the environmental and economic performance of 3D printing technology on a full-scale house and the adoption of 3D printing technology among professionals (Architects and Civil Engineers) in Saudi Arabia. The current research study will attempt to fulfil this gap by assessing the environmental and economic impact of 3D printing technology on a full-scale house. This study will be the first study to be done on a full scale globally, especially in Saudi Arabia. Additionally, the study of the adoption of professionals (Architects and Civil Engineers) will be the first study conducted in Saudi Arabia as the literature reveals that the adoption of 3D printing technology could differ from one country to another. Therefore, three research questions were established to understand the feasibility of adopting 3D printing technology as a new construction method in Saudi Arabia as described in Chapter 1.

2.14. Chapter Summary

This chapter presented an overview of Saudi Arabia and its housing sector development, types of houses in Saudi Arabia, methods and materials used in the construction sector in Saudi Arabia, Saudi building code, houses challenges in Saudi Arabia and Saudi Vision 2030. It also presented 3D printing technology and its different technologies and materials used in construction. Also, it explained the economic aspect of 3D printing technology in construction, the pros and cons of 3D printing technology and innovation theories used to study the adoption of 3D printing technology. This chapter also presented an insight on Sustainability and Sustainability Development, in general, and in construction, particularly. This insight was done by understanding the impacts of construction on the environment using the different methods and tools used to evaluate the environmental performance of buildings. Furthermore, it presented the use of the Life Cycle Assessment (LCA) method in both Saudi Arabia and the 3D printing technology. Finally, this chapter summarised the findings from the literature, emphasised the limitations of the previous studies and distinguished the gap in knowledge and the research questions that will lead the researcher towards uncovering new knowledge.

Chapter 3: Research Design and Methodology

3.1. Introduction

This research began by discovering Saudi Arabia and its housing sector issues, 3D printing technology and its capabilities, and sustainability. Hence, this study aims to investigate the potential of leveraging 3D printing technologies as a new construction method in Saudi Arabia. This investigation will be based on comparing 3D printed technology and conventional construction methods in terms of the environmental, economic, and professional aspects. Furthermore, based on this aim, the research questions and objectives were defined and presented in Chapter 1. These research questions provided a foundation for designing the research methodology. The review of the literature was done to assist in the selection of the most appropriate methodology for the analysis.

This chapter proposes the primary methodological context for the research. It starts with introducing an extensive understanding of the research philosophy, research approach, research methodology and methods, and the justification of the chosen method. Furthermore, this chapter presents the description of the research parts. The first part is “A Comparison Study (LCA) of Conventional and 3D Printing Construction Methods for a Domestic Vila in Al Khobar, Saudi Arabia”. This part starts with presenting Life Cycle Assessment (LCA) as a tool for environmental assessment. Then, it describes the data collection and analysis process for the environmental assessment.

Likewise, the second part is “A Cost Analysis Study of Conventional and 3D Printing Construction Methods”, which describes how the economic benefit will be evaluated when comparing 3D printing technology methods with conventional construction methods. The last part is the “Analytic Study of Construction Industry Perception of 3D Printing Construction Method”, which presents the Diffusion of Innovations Theory (DIT) as the chosen theory for this study. Furthermore, this part will describe the questionnaire design, translation, pilot study, validity and reliability, sampling size, ethical consideration, data collection technique, and data analysis.

3.2. Research Design and Methodology

3.2.1. Research Philosophy

Research has been described as an action that includes "finding out, in a systematic way, things you did not know" (Nicholas 2010). In 2004, Kothari defined research as an objective and systematic method to search for information or verify a viable solution to a specific problem. The contribution of various kinds of research to the body of knowledge within its field includes study, comparison, observation, and experimentation (Kothari 2004; Cross 1999).

To apply the above process to science, the researcher depends on theories and principles that essentially impact the research method and could be written in—what is known as—a research paradigm (Fellows and Liu 2008). A research paradigm is a way for researchers to look at events through the lens of a theory or a set of rules, as Maxwell (2008) defines the paradigm as "a set of very general philosophical assumptions about the nature of the world (ontology) and how we can understand it (epistemology)". Furthermore, another definition describes research paradigm as its ability to create a framework of philosophical principles and assumptions about how the world is observed, which, in turn, guides and enlightens the performance of the researcher and helps the researcher in explaining the nature of probable research and intervention (Jonker and Pennink 2009; Mingers 1997). According to Jonker and Pennink (2009), even though the fundamental research philosophy usually remains more implied than explicitly articulated in most research, these beliefs and principles can deeply influence the real practice of research.

(Figure 3-1) shows the 'research onion', which presents the stages of development of a research project involving a series of theoretical options managed by a specific point of view of the connection between knowledge and the research progress itself (Saunders et al. 2009). In addition, the research paradigm is the first topic that needs to be developed in the research methodology as it is located at the first stage of the 'research onion' (Figure 3-1). Numerous paradigms of research philosophy that may be related to science and knowledge must be considered while forming the study approach and methodology. The philosophy of the paradigm consists of positivism, realism, interpretivism and pragmatism (Saunders et al. 2009). Choosing a specific philosophy for a research paradigm is affected by other aspects, for instance, the practical implications of the research (Saunders et al. 2009). Teddlie and Tashakkori (2010) suggest that paradigms are vital in guiding research. The selection of such a paradigm was based on the research aim, objectives, and questions, which were derived from the purpose and problems for the current research. This study applies a positivist research philosophy. According to Rose et al. (2015), positivism is a philosophical phenomenon that employs natural science approaches in the social sciences, whereas Robson (2011) observes positivism as a previous philosophical perspective of natural science.

Thus, the justification for this choice is that positivism includes developing knowledge achieved by measurement. The chosen paradigm dominates most of the quantitative research. Positivism obtains factual data, which are later examined against former theories or literature to investigate their connections (McGraw and Creswell 2009; Fellows and Liu 2008). This study focuses on the visible phenomenon that can be numerically measured and monitored. In summary, Kothari (2004) believes that positivist studies generally use a deductive approach associated with a phenomenological philosophy.

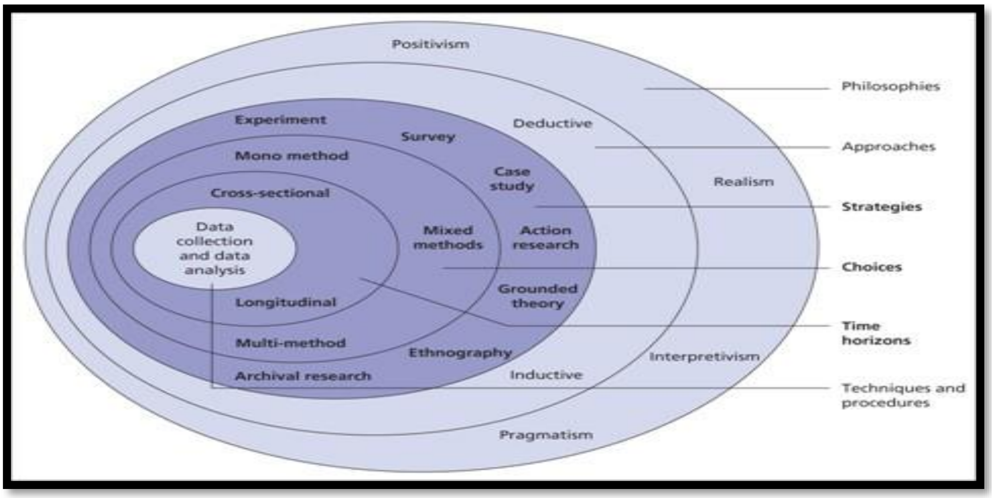


Figure 3-1 Research Onion (Saunders et al. 2019).

3.2.2. Research Approach

The research approach indicates the method in which the research is organised, and is generally distributed into three categories: deductive, inductive, and abductive (Nicholas 2010). These approaches define how the relationship between the research and theory of each approach can be perceived. Furthermore, these approaches can be recognised in theory testing and development, such that, the research could begin with testing an existing theory and end by building a new theory (Bryman 2012; Nicholas 2010), thus emphasising that the deductive approach scrutinises the hypotheses or theories fixed deeply in any hypotheses. By applying the deductive approach, the researcher, in the beginning, generates numerous theories and assumptions relying on hypotheses and theoretical structures. Subsequently, the theory leads and effects the data collecting and studying process. The research tests the theories of the assumption by validating, contradicting, or even changing them (Bryman and Bell 2015). According to Jonker and Pennink (2010), quantitative research is usually connected with the deductive approach. For example, the collected data will be analysed based on quantitative numerical data such as surveys, environmental performance, and energy consumption.

Neuman (2013) defines the inductive approach as creating or asserting a theory that begins with actual practical data and generalises the developed constructs. The inductive approach has the power to direct researchers to new theories development (Nicholas 2010). Furthermore, this approach generally focuses on investigating former research phenomena from another perspective (Kothari 2004). Qualitative research is frequently connected with the inductive approach (Jonker and Pennink 2010).

Finally, an abductive approach refers to “the process of facing an unexpected fact, applying some rules, and as a result, posting a case that may be true” (Johansson 2003). subjectivity and objectivity of social life are fundamentally combined in this approach (Blaikie 2007). This research adopts the deductive approach, which agrees with the research questions, aim, and objectives. Even though literature review is believed to be an inductive research practice, it will not affect the chosen approach.

3.2.3. Research Methodology and Methods

There is a difference between research methodology and research methods, and it is essential to explain these terms and contrast them (King 1994). A research methodology is a broad framework that assists the essential assumptions related to a paradigm for research (O'Leary 2017). It can also be described as a "philosophical framework within which the research is conducted or the ground upon which the research is based" (Collins et al. 2004). In contrast, research methods are the numerous techniques and processes applied in conducting research (Kothari 2004). Also, Creswell (2014) uncovered the three common research methodologies and related methods: quantitative, qualitative, and mixed methods. Usually, research methods are primarily quantitative and qualitative (Onwuegbuzie and Leech 2005). These methods include the process of data collection, analysation, and explanation. Both quantitative and qualitative methods are essential and continuously used by researchers (Onwuegbuzie and Leech 2005; Myers 2009).

Quantitative Research Method

Quantitative research in general observes a continuous stage of formulation of the hypothesis, data collection, data analysis, and finally data explanation (Huysamen 1997). This research method is believed to be experimental research that is deductive (Saunders et al. 2009). Quantitative research methods consist of numbers and variables that are evaluated and examined statistically (Denzin and Lincoln 2000), and usually, they assess the measurement procedure of collecting and analysing data. In addition, the fundamental procedures of quantitative research methods for data collection are surveys and experiments. This research method is applied mostly for statistical outcomes from experiments and questionnaire surveys that help researchers collect numerical data for statistical assessment and studies (Myers 2009). This method needs to achieve a larger sample size than qualitative research methods (FELLOWS and LIU 2015; Neuman 2013). Quantitative research methods can commonly be utilised to assess questions or assumptions against a set of variables in social science research (Blaikie 2003).

Qualitative Research Method

A qualitative research method is identified as discovering the individual's implication of every perception of the research problem (Creswell 2014). This method determines and signifies the clarification and understanding of others to determine problems of inadequate knowledge. It might be performed by utilising opinions, views, reviews, direct documents, and explanations that design data in words (Denzin and Lincoln 2005; Domegan and Fleming 2007). Even though, social science studies have constantly applied qualitative research methods (Neuman 2013). Bryman (2012) states that qualitative research methods usually concentrate on words (non-numeric form) rather than the process of quantification that focuses on collecting and analysing data. Qualitative research methods typically adopt case studies as the initial form (CRESWELL and CRESWELL 2017). Lastly, Gray (2017) believes that this research method is less reliable and valid than quantitative research methods, in general.

Mixed-Method

Qualitative and quantitative methods are both used in mixed method. The use of both qualitative and quantitative methods for data collection and analysis in this method helps to better understand the research problem (Creswell 2014). Teddlie and Tashakkori (2010) definition for mixed method as "the broad inquiry logic that guides the selection of specific methods, and that is informed by conceptual positions common to mixed methods practitioners." It is well-known as a third research method that mixes both the previous methods (Johnson et al. 2007). According to Maxwell (2008), the mixed method pursues precise and complete information that presents a triangulation. To conclude, Kumar (2014) states that the result of adopting different research methods can be utilised to evaluate, contradict, or prove the study's claims.

Choosing a Quantitative Method Approach

Usually, a quantitative research method delivers a broad knowledge of the subject matter. A qualitative research method, on the other hand, provides specificity and intense detail to the research outcomes (Denzin and Lincoln 2005; Myers 2009). Nevertheless, the selection of the research methods has to be designed for achieving effective philosophical outcomes that draw attention to the research questions (Patel 2006). The discoveries of quantitative research allow the researchers to generalise the impact amongst the study population (CRESWELL and CRESWELL 2017). This study aims to investigate the potential of leveraging 3D printing technologies as a new construction method in Saudi Arabia.

Essentially, this study applies a quantitative method in data collection. Such a method includes numerous research strategies involving surveys and new experiments (Saunders et al. 2012). In comparison, a "multi-method quantitative analysis" was chosen as a methodological strategy to achieve the current study. This is done by using a case study and survey as a methodological choice to get the main research data for testing and observing the feasibility of 3D printing as a new construction method in Saudi Arabia. The research plan was divided into three parts to accomplish the research aim and objectives and answer the research questions. A specific methodological strategy is used in each part.

3.3. Research Parts and Descriptions.

After presenting an overview of the research philosophy and the methodological approach, this section will comprehensively examine three parts according to the Triple Bottom Line (TBL) model: an environmental assessment (LCA) of conventional and 3D printing construction methods for a domestic villa in Al Khobar, Saudi Arabia; an economic analysis study of conventional and 3D printing construction methods for the same villa; and an analytic study of a professional's perception of the 3D printing construction method in Saudi Arabia. Each approach will establish its specific method and technique to achieve specific objectives (Figure 3-2).

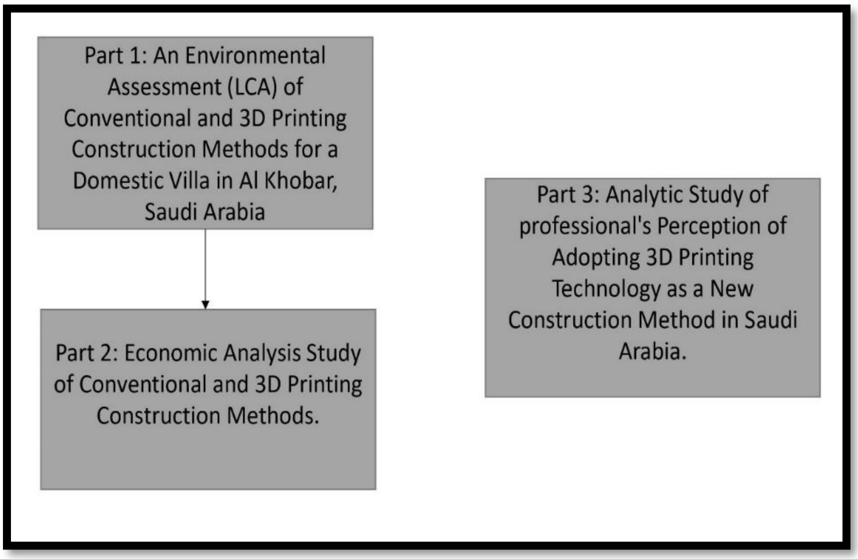


Figure 3-2 Research Parts.

3.3.1. Part 1: A Comparison Study (LCA) of Conventional and 3D Technology Printing Construction Methods for a Domestic Villa in Al Khobar, Saudi Arabia

- Life Cycle Assessment (LCA)

Choosing a proper method and the right tools can be helpful while calculating and comparing the environmental impact of services and products to accomplish sustainable development (Rebitzer et al. 2004). (ISO 14040 2006) defines LCA as "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system". Moreover, Ciambrone (1997) defines (LCA) as being as an environmental performance method that studies, analyses and evaluates the products and their processes from "cradle to grave". This tool involves studying the extraction of raw material, manufacturing, usage, disposal, and recycling (Carvalho et al. 2014). The results presented in LCA for the environmental impact depend on the input (sources and energy consumption), output (water, emissions to air, and land), and materials (Carvalho et al. 2014; Parsons 2016). LCA can be used for product evaluation in more than one aspect, such as the evaluation of the supply chain, eco-design, green procurement, and eco-labelling systems, whereas the results of this evaluation might be used in sustainable strategy analysis, environmental management, and policymaking (Guinee 2002). Thus, it is built on the energy and mass balance rule (Finnegan 2004). LCA is currently being applied in industry to discover the life-cycle phases of products contributing to environmental pollution, for instance SO2, NO2, CO2 and further GHG emissions (Ainger and Fenner 2014).

The rationale behind choosing LCA as an environmental assessment method is to evaluate the product and its process during its whole life cycle phases (raw material, transportation, manufacturing, using phase and final disposal).

environmental impact of products and processes during the entire life cycle stages (raw material, transportation, manufacturing, using phase and final disposal). Further environmental assessment methods such as the environmental impact assessment (EIA) are more appropriate for the assessment of a whole project from an environmental, economic, plans, and policies, which doesn't serve the objectives of this study (Morgan 2012; Tukker 2000). Additionally, LCA has been accepted internationally and the vast majority of industries have become interested in LCA, including the construction industry, which has an interest in searching for increasing resource conservation and sustainability (Sharrard et al. 2008; Kucukvar and Tatari 2013; Buyle et al. 2013).

Over the last 20 years, LCA has been broadly used to assess the impact of buildings, construction materials and components (Hoxha et al. 2017). The LCA methodology demonstrates some challenges which involve the lack of method consistency, lack of data accuracy, the availability of data, the effect of using different impact assessment methods and the interpretation of results (Crawford 2011; Dixit et al. 2012; Finnveden et al. 2009).

History of LCA

The Department of Energy in the United States (US) was the first to report Life Cycle Assessment (LCA) in the 1960s, and it mainly focused on the "fuel cycle" or the calculation of energy requirements (Curran 1996). In 1969, the Coca-Cola Company was the first company to conduct LCA to assess the environmental impact of different containers and termed it “Resource and Environmental Profile Analysis” (REPA) (Hunt and Franklin 1996). Additionally, during 1969 and 1972, LCA was exclusively used for energy and solid waste while related emissions were excluded (Baumann and Tillman 2004). Between 1990 and 1993, the US Society of Environment Toxicology and Chemistry (SETAC) published several aspects of LCA (Klöpffer 2006).

These aspects included: Guideline for Life-Cycle Assessment: A ‘code of Practice’, Conceptual Framework for Life-Cycle Data Quality, Conceptual Framework for Life-Cycle Impact Analysis, Life-Cycle Assessment, and Technical Framework for Life-Cycle Assessment. Shortly after SETAC published these aspects, the International Organisation for Standardization (ISO) joined and worked on developing these procedures and methods in LCA. This resulted in the ISO 14040 series that was published in 1997 (Pryshlakivsky and Searcy 2013). This series included: ISO 14041: Life-Cycle Assessment Goal and Scope definition/Impact analysis Phases, ISO 14042: Life-Cycle Impact Assessment phase and ISO 14043: Life-Cycle Interpretation (Pryshlakivsky and Searcy 2013). The 1997 ISO 14040 series was replaced with principles and framework (ISO 14040 2006) and requirements and guidelines (ISO 14040 2006; Pryshlakivsky and Searcy 2013).

LCA Framework

According to (ISO 14040 2006), LCA involves four phases that work in an iterative process: Goal and Scope Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. Each of these phases are explained deeply in details bellow (Figure 3-3).

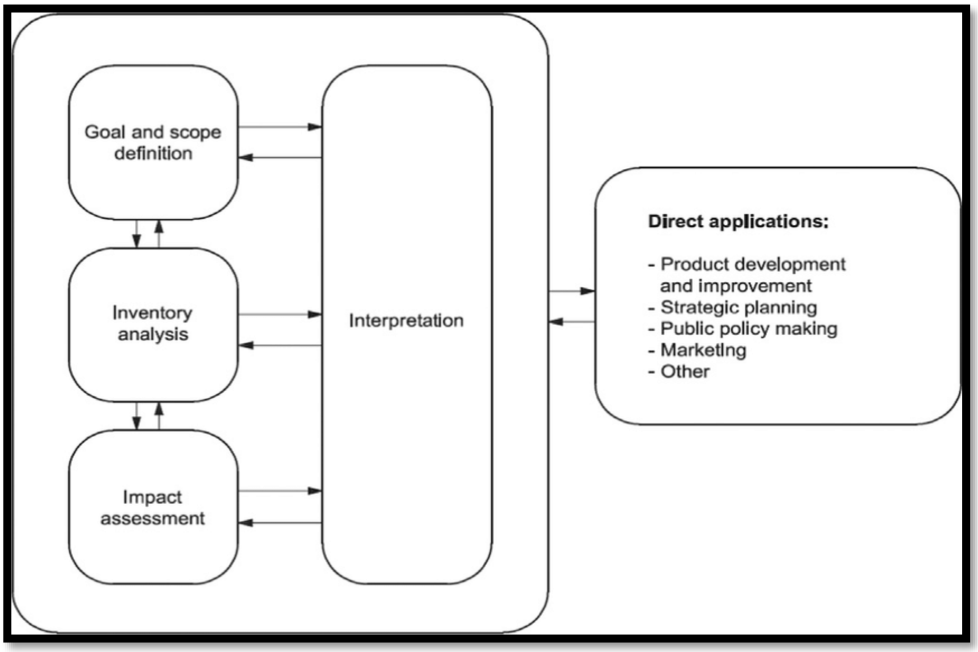


Figure 3-3 LCA Framework (ISO 14040 2006).

Goal and Scope Definition

General

The goal and scope definition helps retain the stability of LCA and serves as the guide for the whole LCA (Goedkoop et al. 2016). It explains the purpose of the study, the description of the product, the description of the system boundary, the functional unit, data requirement and quality, the proposed audience, and the way of sharing results (Goedkoop et al. 2016; ISO 14040 2006). Sometimes, this phase might be modified due to unexpected restrictions, additional information, or constraints (ISO 14040 2006). The goal of this LCA study is to compare and measure the environmental impact of two different construction methods: conventional construction and 3D printing methods. This study will be done on an existing villa in Al Khobar City in Saudi Arabia that was obtained from a Saudi architecture and construction firm named Design Concept.

The LCA study will be done for the same villa in four scenarios. The first two scenarios are conventional construction techniques, and the other two are 3D printing technology construction techniques. Moreover, the first scenario will consider the actual construction of the villa, which includes blockwork walls and reinforced concrete structures (beam and column). This type of construction is most used in Saudi Arabia as mentioned previously in the literature. The second scenario will assume the construction method is the precast construction method. The third scenario will use the 3D printing construction conventional method. Finally, the fourth scenario will be the 3D printing innovative construction method. Further details will be explained in the life cycle inventory.

System Boundary

The processes in the system boundary entail the material flow diagram through the Life Cycle Assessment and should be consistent with the goal and scope (ISO 14040 2006). ISO 14040-2006 indicates that there are three types of system boundaries in LCA:

1- Cradle-to-grave

The cradle-to-grave system consists of the environmental impact of product emissions throughout its life cycle from raw material, transportation, manufacturing of materials, the use phase and final disposal (end of life).

2- Cradle-to-gate

The cradle-to-gate system is the same as the cradle-to-grave system, except not calculating the emissions from the use phase and final disposal (end of life).

3- Cradle-to cradle

The cradle-to-cradle system is the same as the cradle-to-grave system. The difference between them is that in the cradle-to-cradle system the final disposal (end of life) is replaced with recycling.

4- Gate-to-gate

The gate-to-gate system only concentrates on the product production process while taking into consideration the time and geographical boundary.

As previously discussed in Chapter 2, Section 2.8., all the previous studies that used LCA as an assessment method for 3D printing technology used the cradle-to-gate approach. This is due to the current limited information regarding 3D printing technology in construction, thus, this study adopts the second system cradle-to-gate which will cover (raw material, transport, manufacturing of materials and the energy required for construction). Furthermore, this system has a disadvantage which is not covering all stages of the life cycle of the examined product resulting in an incomplete assessment of the product. Surely, using a Gate-to-gate system boundary will offer better environmental assessment results.

Functional Unit

The functional unit ensures an accurate comparison by presenting the quantification for the input and output values (ISO 14040 2006). The ISO 14040 only offers general guidance for choosing a functional unit, which presents a challenge when choosing a functional unit in LCA. It is important to select a functional unit that is measurable and well-defined, as well as consistent with the goal and scope of LCA (ISO 14040 2006). Moreover, Reap et al. (2008) discuss the three areas that can increase the chances of decreasing the error in selecting a functional unit. These include the phases of identifying the functional unit, selecting, and identifying functions and defining the reference flow. Nevertheless, the selection of the functional unit can be difficult for multiple systems (Bayer et al. 2010; Cooper 2003). The functional unit for this study was based on earlier research (Agustí-juan et al. 2017; Cuéllar-Franca and Azapagic 2012; Jia Wen et al. 2015). Thus, the functional unit for this study will measure one square meter ($1m^2$) of the building's gross floor area (GFA). There might be a slight difference in the GFA in the four scenarios due to the structural/physical properties of each method.

Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) is the phase that considers inputs and outputs combined with the products and the functions that quantify the environmental burdens. This is produced from all processes contained by the specified boundaries in the goal and scope phase (Rebitzer et al. 2004). The environmental problems consist of emissions to water, solid waste, and air (Baumann and Tillman 2004). LCI is considered to be a challenging task among all of the phases, wherein, for the preparation of the LCA study, this phase is time, data, and labour intensive (Finnveden et al. 2009; Rebitzer et al. 2004). Goedkoop et al. (2016) state that the data required for this phase entails two types of systems: A foreground system, which involves specific data for processes or operations and a background system, which provides the necessary material such as transport, waste management system and energy. In contrast, operations and processes for the individual plant are unidentifiable (Tillman 2000). There is more than one way to collect the data, such as companies, governments, factories, commercial databases, and contractors (Du and Karoumi 2014). In the building sector, the bill of quantities is considered to be one of the most effective ways to collect data (Rosli et al. 2006). The researcher should be careful when collecting the data because the quality of data will affect the LCA results consistency (Khasreen et al. 2009). (Table 3-1) shows a summary of the usually used databases in the field of construction around the world.

Table 3-1 LCA Databases and Tools. Sources Adopted and Revised from (Khasreen et al. 2009) and (Du and Karoumi 2014).

Database	Function	Country	Level	Website
Athena	Database + Tool	Canada	Whole building design decision	http://www.athenasmi.org/
Bath data	Database	UK	Product comparison	https://wiki.bath.ac.uk/#all-updates
BEES	Tool	USA	Whole building design decision	https://www.nist.gov/services-resources/software/bees
BRE (Building Research Establishment)	Database + Tool	UK	Whole building design decision	https://www.bregroup.com
Boustead	Database + Tool	UK	Product comparison	https://www.webku.net
Eco invent	Database	Sweden	Product comparison	https://simapro.com/databases/ecoinvent/
Gabi	Database + Tool	Germany	Product comparison	https://gabi.sphera.com/uk-ireland/index
IO-database	Database	Denmark	Product comparison	----------------------------

IVAM	Database	Netherlands	Product comparison	www.ivam.uva.nl/index.php?id=lcadatabaseandL=1
Optimize	Database + Tool	Canada	Whole building design decision	----------------------------
SimaPro	Database + Tool	Netherlands	Product comparison	https://simapro.com
Spin	Database	Sweden	Product comparison	----------------------------
Umberto	Database + Tool	Germany	Product comparison	https://www.ifu.com/umberto
US LCI data	Database	USA	Product comparison	https://www.nrel.gov/lci

Villa scenarios used for data collection and analysis

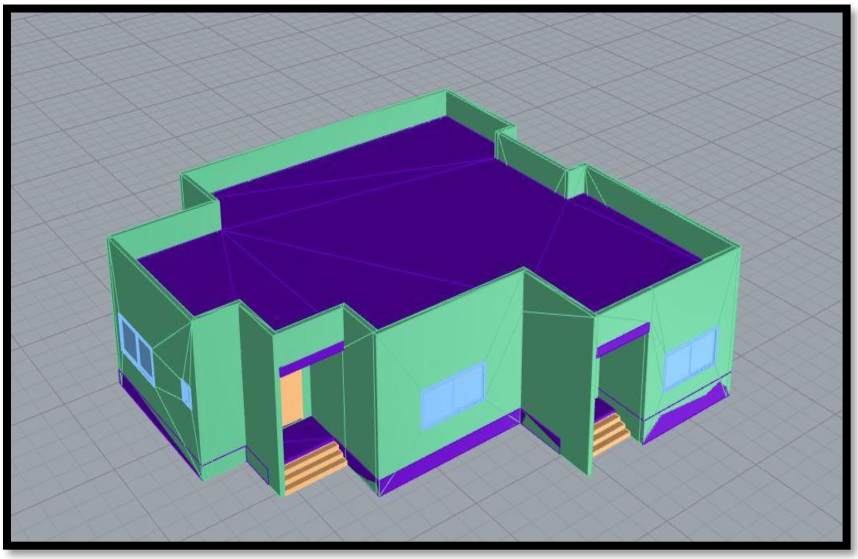
This section presents four scenarios of one villa: conventional villa, precast villa, 3D printing standard villa and 3D printing innovative villa. Furthermore, each scenario will be discussed separately and shows the sources of data collection and the instruments used. The related information and the calculation details for all the scenarios can be found in Appendix A.

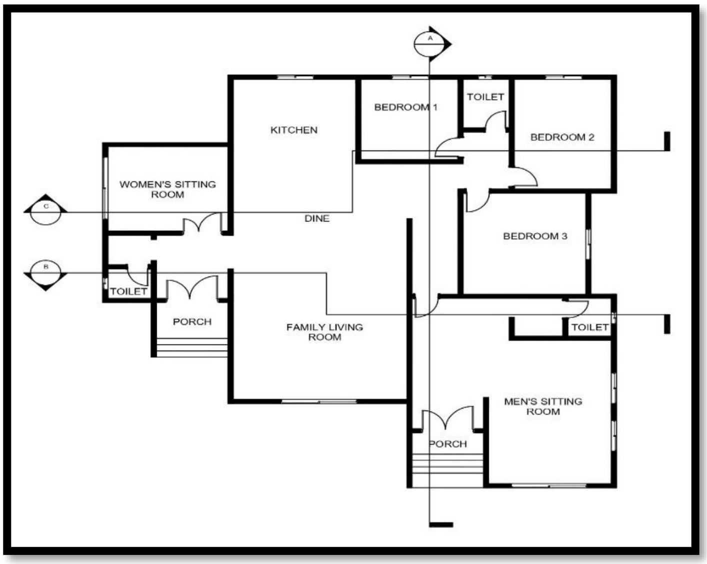
Scenario one: Conventional villa

The chosen villa for this study is a one-story villa in Al Khobar in the eastern part of Saudi Arabia. Since the housing construction system in Saudi Arabia is the same, choosing any city will not make a difference. Furthermore, the location was chosen because it was the researcher's only place to obtain the project. The bill of quantities was obtained from an architectural firm that designed and constructed the project (Design Concept) (Figure 3-4) and (Table 7). The villa has an area of 310 m^2 with five bedrooms, one living and dining room, a kitchen and three toilets. (Table 3-2) presents the description of the villa.

Table 3-2 Description of Conventional Villa.

Building information	Description
Location	Al Khobar, Kingdom of Saudi Arabia
Shape	Square
Ceiling Height	3.20 m
Floor Area	310.00 m2
Window Wall Ratio	10%
Foundation	R.C Raft
Flooring	400mm x 400mm x10mm Ceramic Tiles
Exterior Walls	200mm x 400mm x 200mm isolated block
Interior Walls	200mm x 400mm x 200mm block
Roof	Reinforced Concrete Slab, insulated with water /thermal proofing
Windows	6mm double glazed aluminium sliding window
HVAC	Split Type




A
KITCHEN
BEDROOM 1
TOILET
BEDROOM 2
WOMEN'S SITTING ROOM
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DINE
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MEN'S SITTING ROOM
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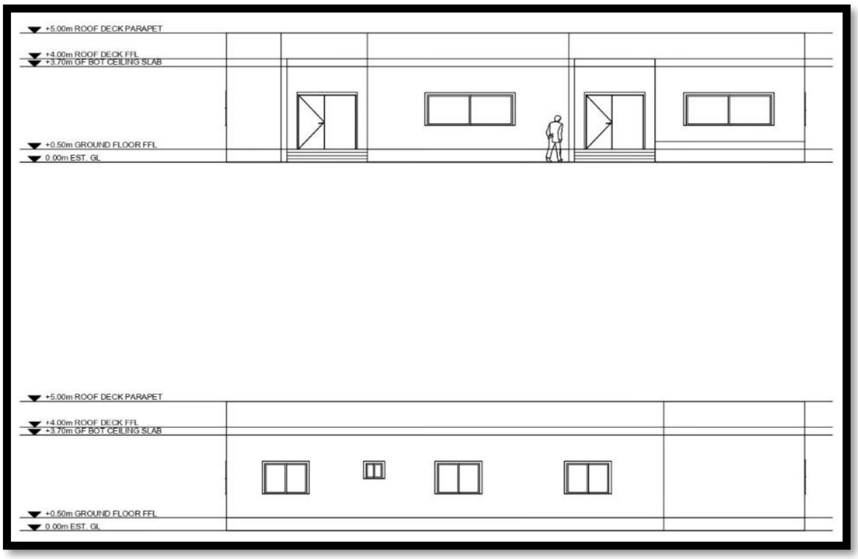
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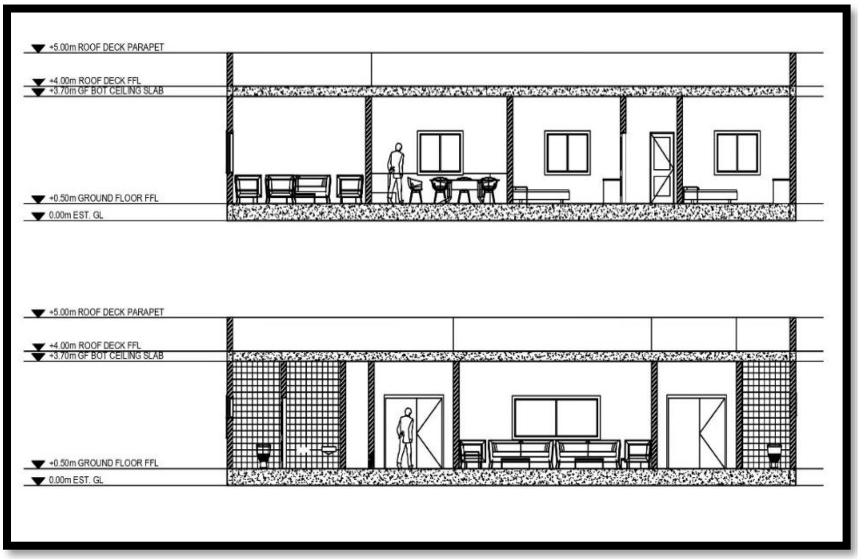


Figure 3-4 Conventional Villa.

Table 3-3 Bill of Quantities for Conventional Villa.

	Material/ Component	**Usage**	**Quantity**	
			Amount	**Unit**
1	Concrete	Ready mix concrete (roof, columns, beams, footings)	**401.68**	**m3**
2	Steel bars	Footings, columns, beams, slab	**52.72**	**ton**
3	Concrete masonry units (CMU)	Exterior and interior walls and U.G. masonry	**6,972.25**	**Pcs**
4	Glass	Windows	**0.28**	**m3**
5	Aluminium	Framing	**64.80**	**l.m**
6	Wood	Doors	**1.30**	**m3**
7	Ceramic tiles	Room tiles	**270**	**m2**
8	Ceramic flooring tiles	Bathroom and kitchen floor tiles	**37.00**	**m2**
9	Ceramic walling tiles	Bathroom and kitchen wall tiles	**116.32**	**m2**
11	Mortar	Exterior and interior walls	**28.47**	**m3**
12	Gypsum	Ceiling	**3.68**	**m3**
13	Polystyrene (EPS)	Thermal insulation for roof slab	**15.50**	**m3**

	Material/ Component	Usage	Quantity	
			Amount	Unit
15	Polyethylene	Vapor barrier (foundation)	**0.16**	**m3**
16	Bitumen Membrane	On top of the roof	**329.69**	**m2**
17	Bitumen Paint	Water proofing (foundation)	**377**	**m2**
18	Paint			
19	White Paint	Interior	**774.05**	**m2**
20	Textured Paint	Exterior	**464.30**	**m2**
21	Polystyrene (EPS) inside masonry	Thermal insulation for outer walls	**17.49**	**m3**
22	Polyvinyl chloride (PVC)-plumbing	Sewer line	**280**	**l.m**
		Water line	**780**	**l.m**
23	Wood	Formwork	**5.74**	**m3**

Scenario two: Precast villa

The second scenario is constructing the villa using a conventional construction technique called precast. As presented in Chapter 2, this technique is used in Saudi Arabia in megaprojects such as big real estate development projects (Alabbasi and Chen 2021). The researcher contacted the architectural firm that designed the villa and asked for the help of a civil engineer to design the structural system and provide a bill of quantities for the new design. Moreover, the recommended structural system from the civil engineer was a modular system. This system fabricates the complete unit at a factory and installs on-site, which is useful for smaller single units. This is ideal for individual rooms and toilet blocks as it ensures waterproofing at intersections (Bloks Precast 2020). As for the wall type, a load-bearing wall was recommended. The recommended specification for the wall's width is 20 cm and the walls contain a 10 x 10 cm reinforced mesh (Figure 3-35). The load-bearing wall resists and distributes the load from other components and this wall cannot be removed without damaging the building's stability or strength (Gaudette 2016). The roof system was changed from a 30 cm depth reinforced slab to a 25 cm hollow core slab (Table 3-4) shows the bill of quantities of the precast construction technique for the same villa.

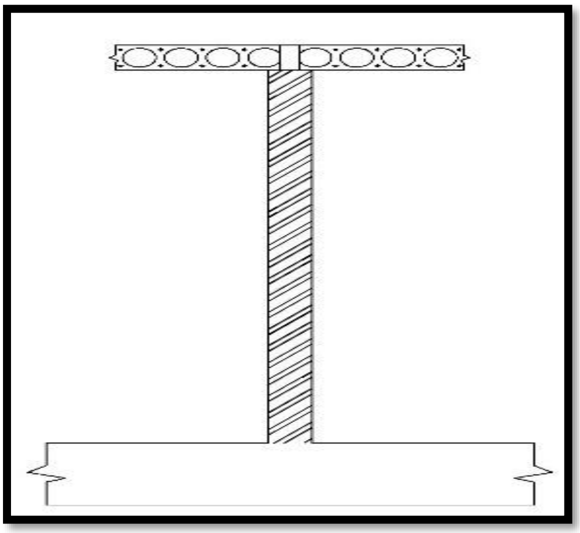


Figure 3-5 Section for Precast Wall.

Table 3-4 Bill of Quantities for Precast Villa.

	Material/Component	Usage	Quantity	
			Amount	**Unit**
1	Concrete	Ready mix concrete (footings)	**240.94**	**m3**
2	Steel bars	Footings	**31.62**	**ton**
3	Precast walls			
4	Concrete	Interior and Exterior walls	**127.10**	**m3**
5	Steel bars	Interior and Exterior walls	**11.04**	**ton**
6	Glass	Windows	**0.28**	**m3**
7	Aluminium	Framing	**64.80**	**l.m**
8	Wood	Doors	**1.30**	**m3**
9	Ceramic tiles	Room tiles	**270.00**	**m2**
10	Ceramic flooring tiles	Bathroom and kitchen floor tiles	**37.00**	**m2**
11	Ceramic wall tiles	Bathroom and kitchen wall tiles	**116.32**	**m2**
12	Gypsum	Ceiling	**3.68**	**m3**
13	Polystyrene (EPS)	Thermal insulation for roof slab	**15.50**	**m3**
14	Polyethylene	Vapor barrier (foundation)	**0.16**	**m3**

	Material/Component	Usage	Quantity	
			Amount	Unit
15	Bitumen Membrane	On top of the roof	**329.69**	**m2**
16	Bitumen Paint	Water proofing (foundation)	**377.00**	**m2**
17	Paint			
18	White Paint	Interior	**774.05**	**m2**
19	Textured Paint	Exterior	**464.30**	**m2**
20	Polystyrene (EPS) inside masonry	Thermal insulation for outer walls	**7.33**	**m3**
21	Polyvinyl chloride (PVC)-plumbing	Sewer line	**280**	**l.m**
22		Water line	**780**	**l.m**
23	Wood	Formwork (footing)	**0.81**	**m3**
24	Concrete	Hollow core slab	**49.04**	**m3**
	Wire strands		**0.77**	**ton**
	Steel bars	Steel net above Hollow-core slab	**2.67**	**ton**
	Concrete	Concrete above Hollow-core slab	**21.73**	**m3**
25	Steel sheet	Formwork in the factory for Interior and Exterior walls	**51.86**	**ton**

Scenario three: 3D Printing standard villa

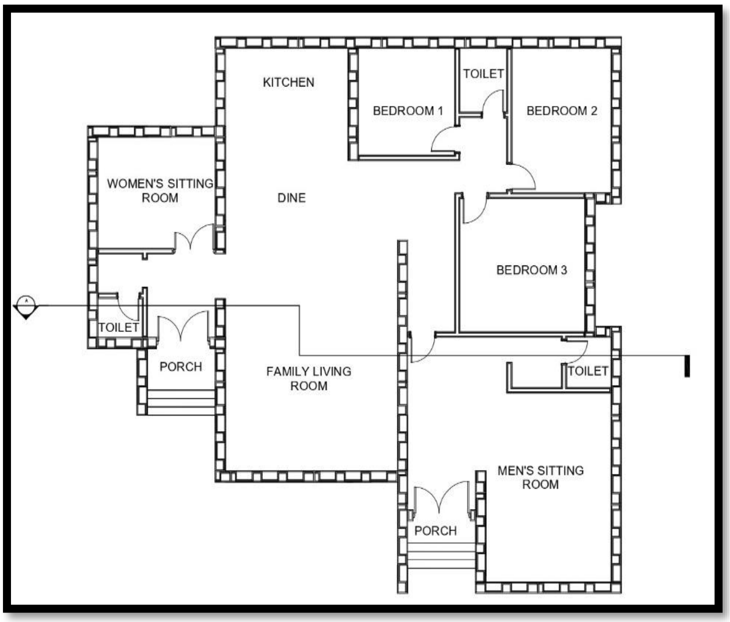
The third scenario is constructing the same villa using the 3D printing technology construction method. The exterior walls, interior walls and the roof were modified according to an existing 3D printed house in Saudi Arabia. The technique and design information were obtained from the Building Technology Program under the ministry of housing in Saudi Arabia. (Figure 3-6) shows the redesign of the villa. The original area for the conventional villa was 310 $m^{2,}$ and after the modification in 3D printing, the area was 326 m^2. The difference in the area was because the width of the outer walls and some of the inner walls shifted from 20 cm to 40 cm. Moreover, the roof system was designed to be a hollow core slab with a depth of 25 cm. The assumed printing machine for this study was KUKA KR 120 R3900 ultra-K. The 3D printed house in Saudi Arabia used the same size robot but from ABB. The researcher contacted ABB company to get more information regarding the robot, but the company did not cooperate. Therefore, KUKA was chosen for this research.

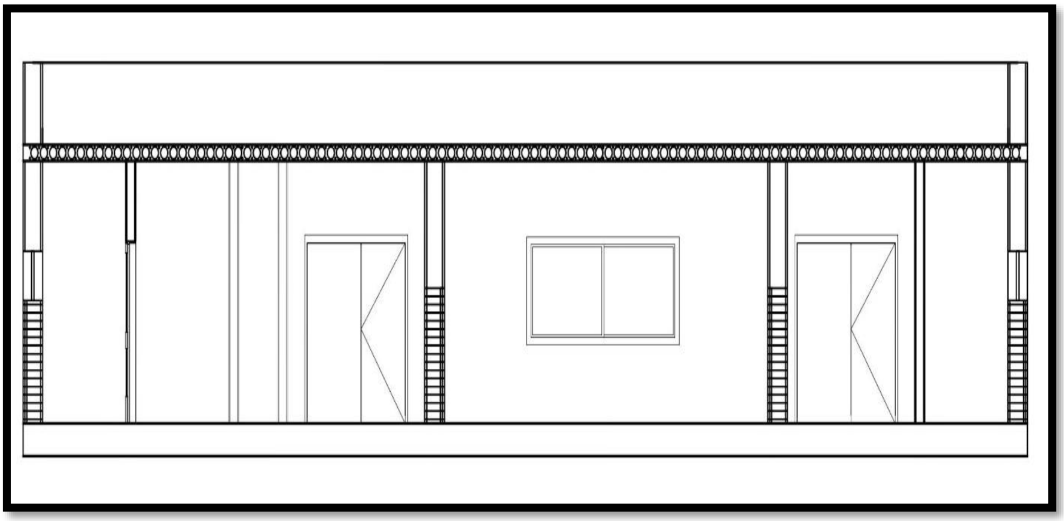
Cement is produced on a global scale at a rate of around 3.5 billion tonnes per year. It is utilised in the production of concrete, mortar, and a variety of other construction products, making it an essential component in the construction industry. However, CO2 emissions from cement production are attracting an increasing level of attention. These emissions are significant, accounting for approximately 7% of the total yearly emissions caused by energy and industry (Fennell et al., 2021). The ratio of cement in 3D printed mixes is usually much higher (25%) than the ratio of cement used in conventional mixes (10-15%). The issue of the high percentage of cement in 3D printed mix was not ignored in this research. First, due to secret trade, the companies that produces 3D printed concrete mix did not share the mix so, there was a need to examen the literature. Second, through the design of the structure, the amount of concrete mix in 3D printing construction is less than the amount of concrete mix in conventional construction. This saving is caused by the design of the 3D printed structure, the reduction of waste in 3D printing construction, and not using formwork in 3D printing techniques.

For the 3D printing concrete mix, previous studies have proposed different ratios of the materials used in the mix of 3D printed concrete (Table 3-5). After a comprehensive examination of the literature (Le et al. 2012), it was found that extensive testing of various 3D printed concrete mixes defines the best usability and workability. Other studies (Buswell et al. 2018; Labonnote et al. 2016; Paul et al. 2018; Ngo et al. 2018; Malaeb et al. 2015; Wolfs 2015) have initially used Le et al.'s (2012) study to conduct their work. Consequently, this LCA study will be conducted with the mix provided by Le et al. (2012). (Table 3-6) shows the bill of quantities for a 3D printing standard villa. The researcher did all the calculations, which the supervisor and the architecture firm revised.

Table 3-5 Ingredients of Different 3D Printing Concrete Mixes from Earlier Studies

	(Nerella et al. 2016)	(Le et al. 2012)	(Anell 2015)	(Agustí-juan et al. 2017)
	%	%	%	%
Cement	19.5	25	30	20.5
Fly-ash	7.7	7.1	4	--
Silica fume	8.1	3.6	4	1.8
Sand/ aggregates	56.1	53.5	52	70.5
Water	8.1	10	10	7
Super plasticiser	0.5	0.7	0.5	0.2
Fibre	--	0.05	0.05	--





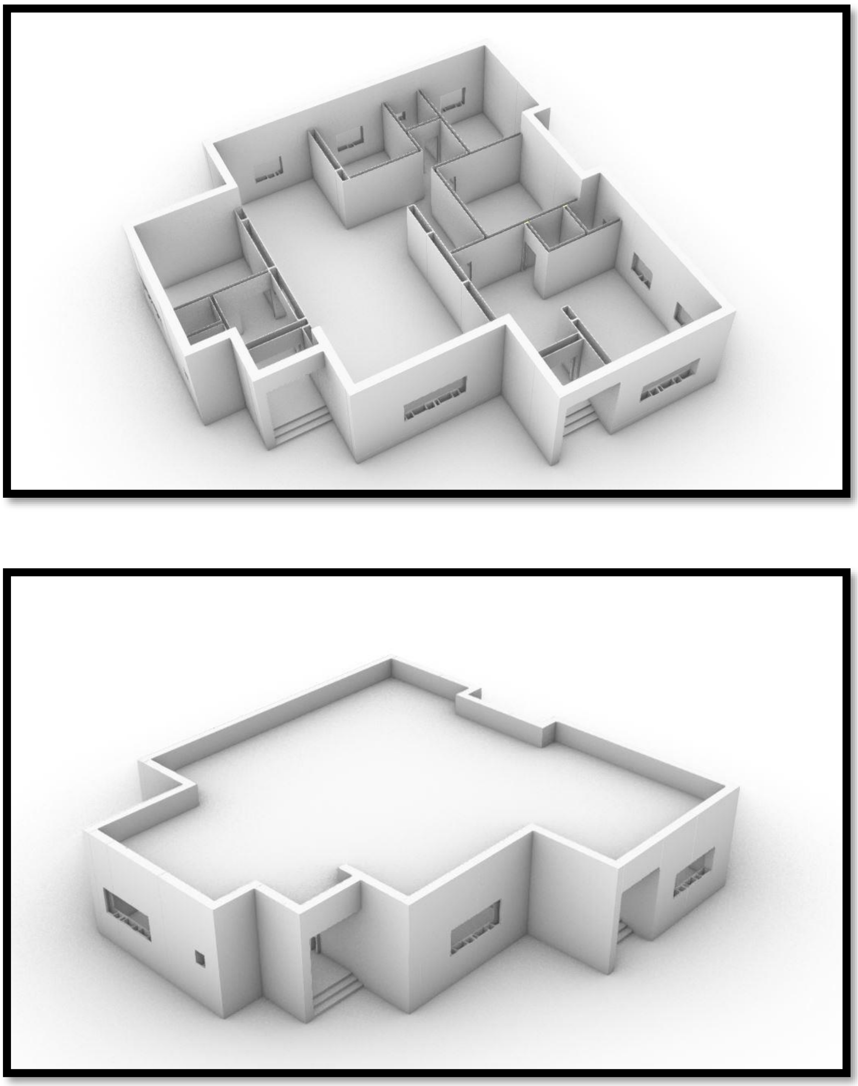


Figure 3-6 3D printed Standard Villa.

Table 3-6 Bill of Quantities for 3D Printing Standard Villa.

	Material/Component	Usage	Quantity	
			Amount	**Unit**
1	Concrete	Ready mix concrete (footings)	**154.50**	**m3**
2	Steel bars	Footings	**19.31**	**ton**
3	Glass	Windows	**0.28**	**m3**
4	Aluminium	Framing	**64.80**	**l.m**
5	Wood	Doors	**1.30**	**m3**
6	Ceramic tiles	Room tiles	**270.42**	**m2**

7	Ceramic flooring tiles	Bathroom and kitchen floor tiles	**36.13**	**m2**
8	Ceramic wall tiles	Bathroom and kitchen wall tiles	**116.13**	**m2**
9	Gypsum	Ceiling	**3.68**	**m3**
10	Polystyrene (EPS)	Thermal insulation for roof slab	**14.68**	**m3**
11	Polyethylene	Vapor barrier (foundation)	**0.17**	**m3**
12	Bitumen Membrane	On top of the roof	**329.12**	**m2**
13	Bitumen Paint	Water proofing (foundation)	**359.26**	**m2**
15	Paint			
16	White Paint	Interior	**768.16**	**m2**
17	Textured Paint	Exterior	**465.22**	**m2**
18	Polyvinyl chloride (PVC)- plumbing	Sewer line	**280**	**l.m**
19		Water line	**780**	**l.m**
20	Wood	Formwork for footings	**0.62**	**m3**
21	Concrete	Hollow core slab	**51.4**	**m3**
	Wire strands		**0.79**	**ton**
	Steel bars	Steel net above Hollow core slab	**2.87**	**ton**
	Concrete	Concrete above Hollow core slab	**23.41**	**m3**

Scenario four: 3D Printing innovative villa

The fourth scenario aims to show the enhancement of current techniques of the 3D printing technology. This is done by optimising the actual villa to enhance time, material, and complexity. The first step was to adjust the plane to show continuity when printing and avoid having 90 degree corners as much as possible (Figure 3-7). Additionally, in a conventional 3D printing standard villa, the wall has a 3D printed zigzag in the middle. While in the new design, the zigzag was taken out and replaced with steel ties of 8mm. This modification was done because the researcher compared a conventional wall with a 3D printed wall using the same pattern (Alhumayani et al. 2020). The study results demonstrated that cement and fly ash had the highest contribution among 3D printing concrete mixes. Likewise, construction material was saved by taking out the zigzag from the middle. A COBOD 2 printer was used instead of a robot arm in this scenario to save time. Robot arms have more flexibility in printing than gantry but have very limited reach (Delgado Camacho et al. 2018). Moreover, COBOD 2 is considered the largest 3D printing in the world (COBOD 2019). The roof system for this scenario is the same roof system that was applied in the 3D printed standard villa.

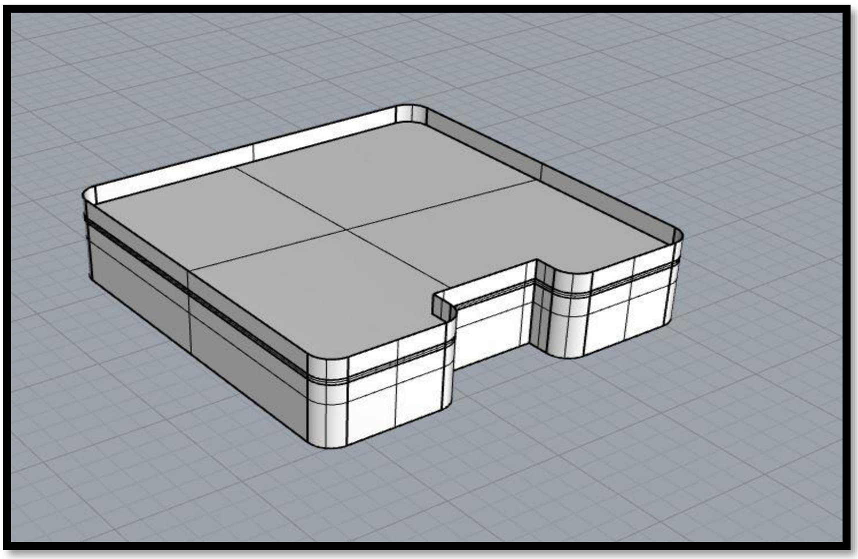


Figure 3-7 The First Step of Designing 3D Printing Innovative Villa.

The 3D printing technology has the advantage of forming more complex shapes than conventional construction methods (Geneidy et al. 2019). To use this advantage, a plug-in in Grasshopper software called Ladybug (Roudsari and Pak 2013) helped generate a new complex shape of the outside layer of the villa. This was done by adding the revised design of the villa and the existing context on the actual location of the villa and running the Ladybug simulation on it (Figure 3-8). Furthermore, after indicating the surfaces that receive most of the sun radiation, points were distributed on the walls and were identified by numbers so each point could be modified. An assumption was made that each point on the optimised walls will start from 0 to 50 cm from the outer wall layer depending on the impact of the solar radiation on each point. At the end of this process, a complex shape was generated, which is shown in (Figure 3-9). Additionally, Arup Group's Civil Engineer Patrick Barry recommended the number of steel ties inside the walls. Patrick provided a Grasshopper code that indicated where the ties should go in each wall (Figure 3-10). Finally, (Figure 3-11) presents the design of the 3D printing innovative villa and (Table 3-7) presents the bill of quantity for the 3D Innovative villa.

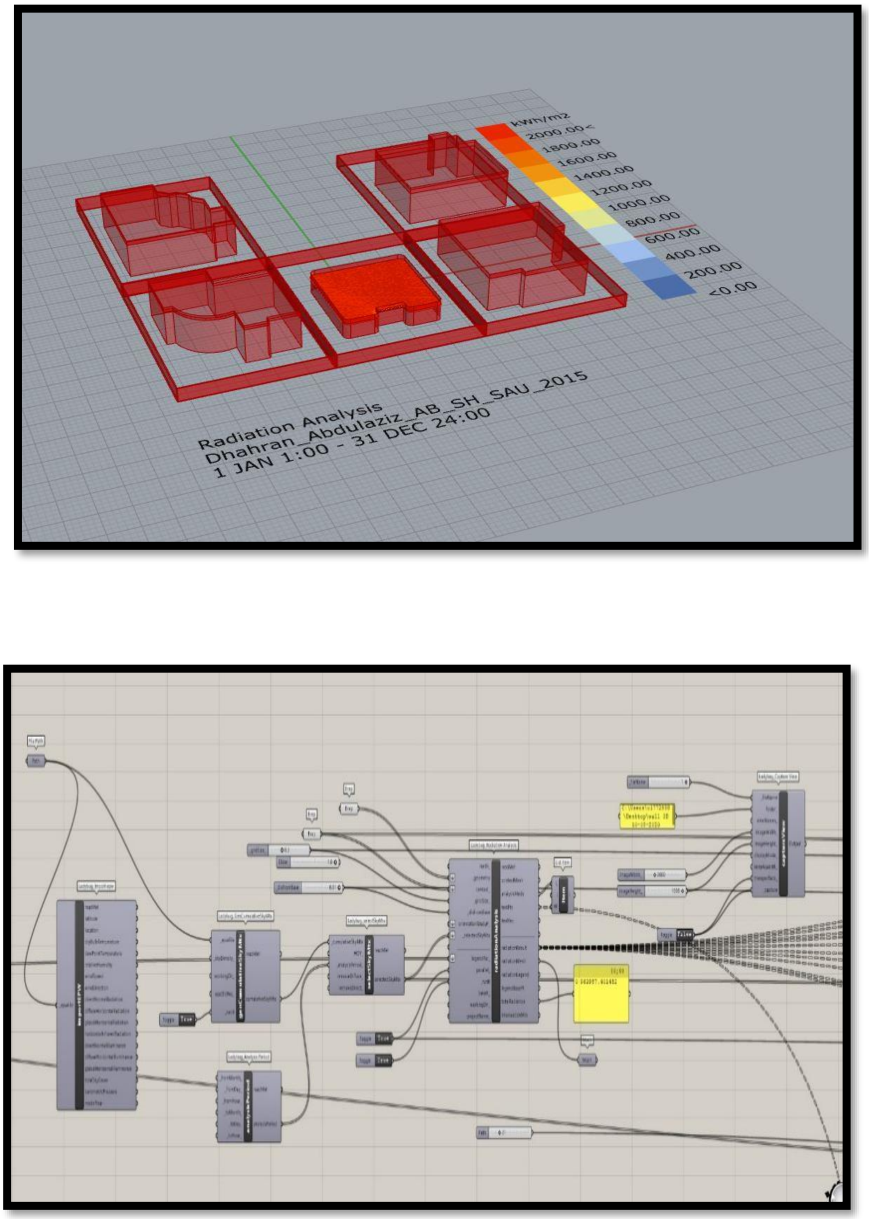


Figure 3-8 Ladybug Simulation.

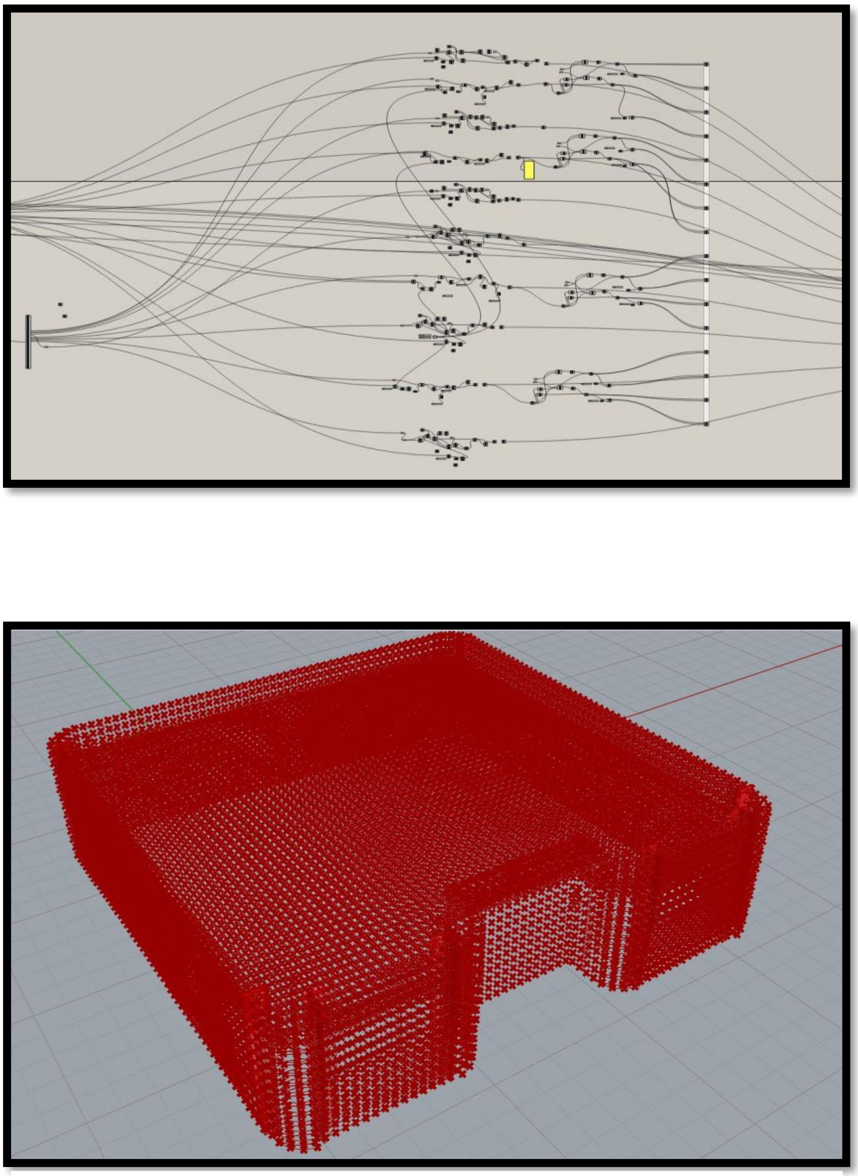


Figure 3-9 Generating Complex Shape.

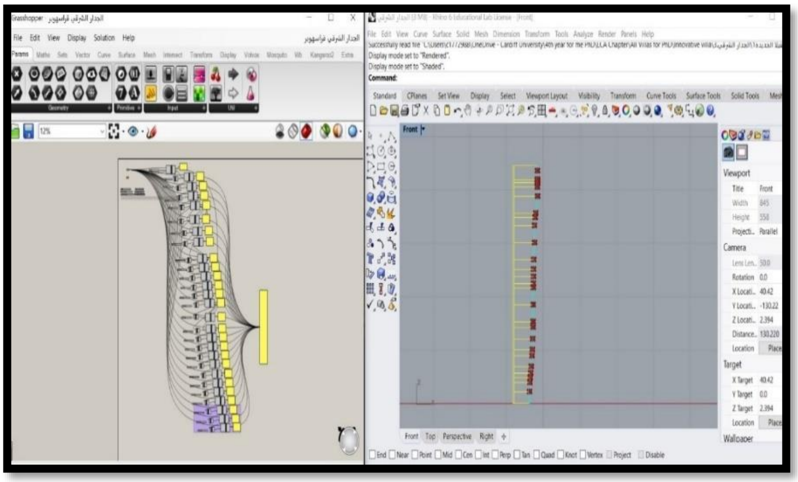
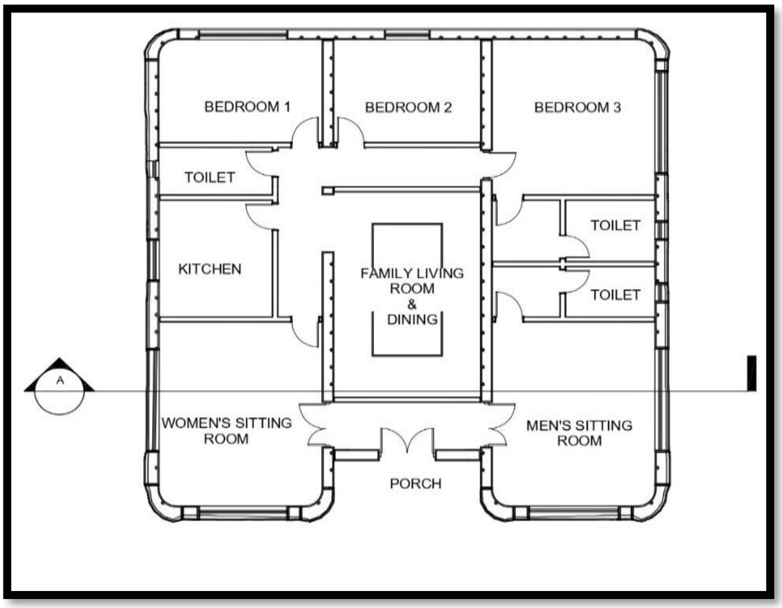
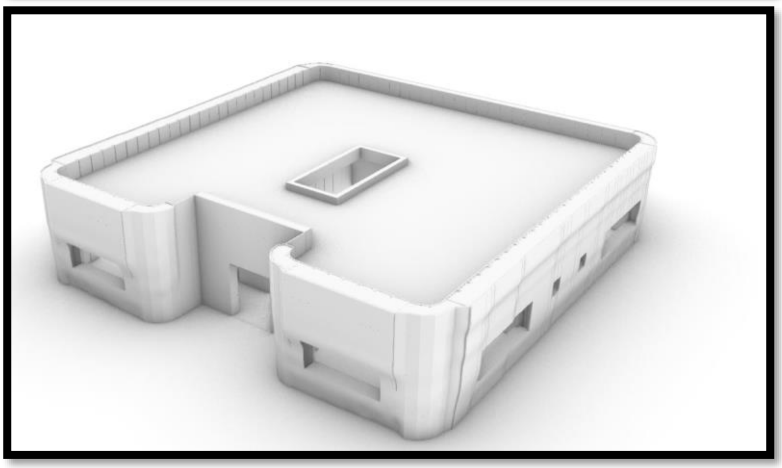


Figure 3-10 Distribution of Steel Ties.





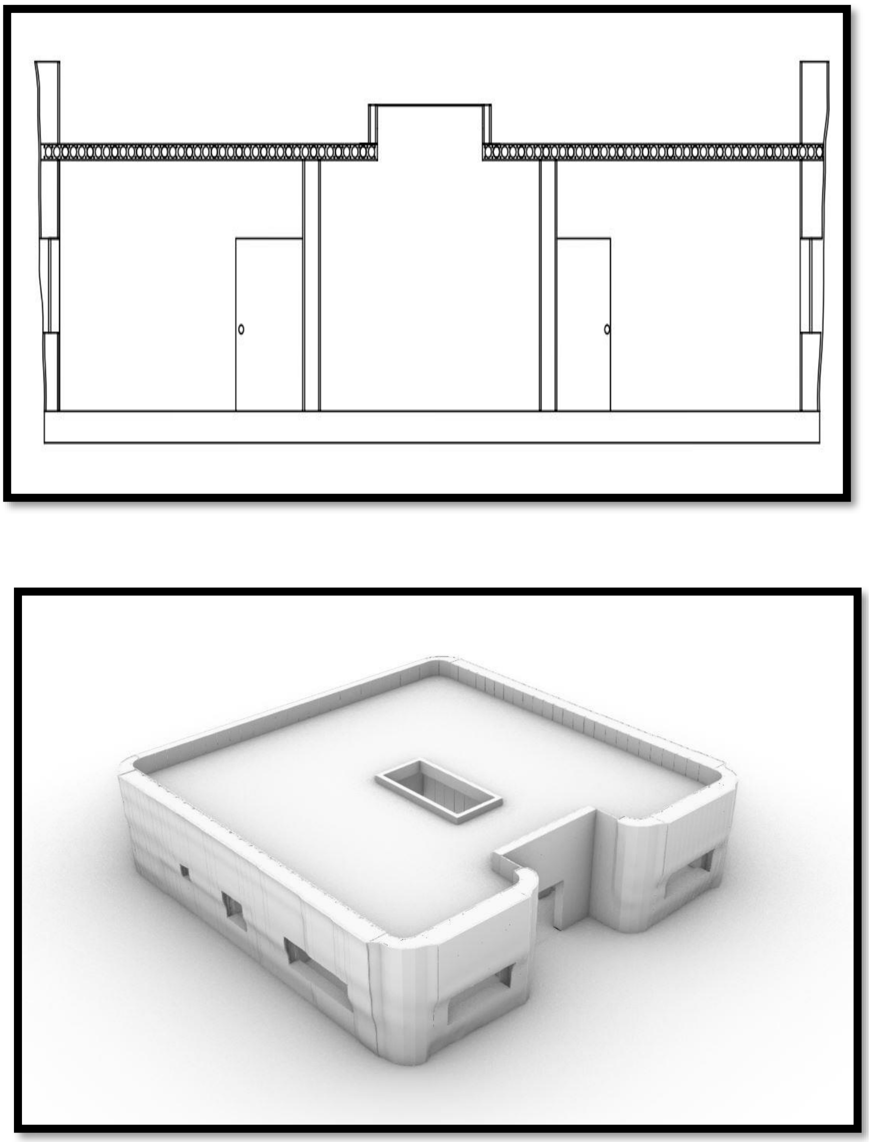


Figure 3-11 3D Printing Innovative Villa.

Table 3-7 Bill of Quantities for 3D Printing Innovative Villa.

	Material/ Component	Usage	Quantity	
			Amount	Unit
1	Concrete	Ready mix concrete (footings)	**143.35**	**m3**
2	Steel bars	Footings	**19.51**	**ton**
3	Glass	Windows	**0.4512**	**m3**
4	Aluminium	Framing	**98.2**	**l.m**
5	Wood	Doors	**1.6515**	**m3**
6	Ceramic tiles	Room tiles	**235.05**	**m2**
7	Ceramic flooring tiles	Bathroom and kitchen floor tiles	**46.79**	**m2**

	Material/ Component	Usage	Quantity	
			Amount	**Unit**
8	Ceramic wall tiles	Bathroom and kitchen wall tiles	**209.46**	**m2**
9	Gypsum	Ceiling	**3.07**	**m3**
10	Polystyrene (EPS)	Thermal insulation for roof slab	**15.03**	**m3**
11	Polyethylene	Vapor barrier (foundation)	**0.15**	**m3**
12	Bitumen Membrane	On top of the roof	**286.58**	**m2**
13	Bitumen Paint	Water proofing (foundation)	**331.14**	**m2**
15	Paint			
16	White Paint	Interior	**729.97**	**m2**
17	Textured Paint	Exterior	**381.58**	**m2**
18	Polyvinyl chloride (PVC)-plumbing	Sewer line	**280**	**l.m**
19		Water line	**780**	**l.m**
20	Wood	Formwork for footings	**0.54**	**m3**
21	Concrete	Hollow core slab	**47.87**	**m3**
	Wire strands		**0.76**	**ton**
	Steel bars	Steel net above Hollow core slab	**2.63**	**ton**
	Concrete	Concrete above Hollow core slab	**21.1**	**m3**

Electricity consumption calculation

There are two approaches for estimating the electricity needed by construction machines throughout the building process: practical and mathematical. In the practical technique, there are two methods to accomplish this: either by estimating the number of full charges required to complete the building process if the machinery is battery-powered, or by employing power/electricity monitors that simply read the source of power for the machinery being utilised (i.e., in this study robotic arm and gantry). The mathematical technique requires knowledge of the Kilowatt-hour (kWh) power ratings of the fabrication equipment and the time required to finish the manufacturing process. Due to the fact that the machines employed in this research use either a direct power supply line or an oil supply, the mathematical technique of computation will be applied. Consequently, the following equation is used to compute total electricity consumption:

$$\text{Electricity (kWh)} = \text{power consumption (kW)} \times \text{Time (hours)}$$

For all scenarios, the chosen truck and pump for this study is VOLVO truck (Volvo 2006). Also, the chosen hollow core slab making machine is Extruder evo Machines (EVO 2021) and for the wire strands machine Prensoland (Prensoland 2019).

Electricity consumption calculation for conventional method

Manual labour does the work in conventional construction; however, in the environmental assessment, human life's energy emissions and requirements are not generally performed (Agustí-juan et al. 2017). Alcott (2012) conducted a study that calculated the human aspect and discovered that its effect was negligible. Therefore, in this research, the human aspect will not be involved. Most of the manufacturing processes were done manually except for the machinery used to manufacture the roof in the precast villa and the concrete trucks and concrete pump for conventional and precast villas. After using the equation above, the electricity consumption for the concrete truck in the conventional villa was 14.64 kWh and for the concrete pump, it was 1740.61 kWh, with the machine working at 50% capacity (Table 3-8) and (Table 3-9).

Table 3-8 Calculation of Concrete Truck Mixer Electricity Consumption for Conventional Villa.

ENERGY CALCULATION		
Concrete volume	401.68	m3
Motion speed	4	m3/min
Total time	100.42	min
Time as hour	1.67	hr
Power as 100%	17.50	kw
Power as 50%	8.75	kw
Power consumption 50%	**14.64**	**kwh**
Power consumption 100%	**29.29**	**kwh**

Table 3-9 Calculation of Concrete Pump Electricity Consumption for Conventional Villa.

ENERGY CALCULATION		
Concrete volume	401.68	m3
Motion speed	0.5	m3/min
Total time	803.36	min
Time as hour	13.39	hr
Power as 100%	260	kw
Power as 50%	130	kw
Power consumption 50%	**1740.61**	**kwh**
Power consumption 100%	**3481.23**	**kwh**

In the precast villa, the electricity consumption for the concrete truck was 16 kWh and for the concrete pump, it was 1901.51 kWh, working at 50% capacity (Table 3-10) and (Table 3-11). The roof system in the precast villa is a hollow core slab system, so the machines' calculation was added to the study. The electricity consumption for the concrete hollow core slab making machine was 54.12 kWh and for the Wire Strands Machine, it was 0.80 kWh (Table 3-12) and (Table 3-13).

Table 3-10 Calculation of Concrete Truck Mixer Electricity Consumption for Precast Villa

ENERGY CALCULATION		
Concrete volume	438.81	m3
Motion speed	4	m3/min
Total time	109.70	min
Time as hour	1.83	hr
Power as 100%	17.50	kw
Power as 50%	8.75	kw
Power consumption 50%	**16**	**kwh**
Power consumption 100%	**32**	**kwh**

Table 3-11 Calculation of Concrete Pump Electricity Consumption for Precast Villa.

ENERGY CALCULATION		
Concrete volume	438.81	m3
Motion speed	0.5	m3/min
Total time	877.62	min
Time as hour	14.63	hr
Power as 100%	260	kw
Power as 50%	130	kw
Power consumption	**803.02**	**kwh**
Power consumption 50%	**1606.04**	**kwh**
Power consumption 100%		

Table 3-12 Calculation of Concrete Hollow Core Slab Making Machine Electricity Consumption for Precast Villa.

ENERGY CALCULATION		
Casting length	267	m3
Motion speed	1.85	m3/min
Total time	144.32	min
Time as hour	2.41	hr
Power as 100%	45	kw
Power as 50%	22.50	kw
Power consumption 50%	**54.12**	**kwh**
Power consumption 100%	**108.24**	**kwh**

Table 3-13 Calculation of Wire Strands Machine Electricity Consumption for Precast Villa.

ENERGY CALCULATION		
Casting length	267	m3
Motion speed	36	m3/min
Total time	7.42	min
Time as hour	0.12	hr
Power as 100%	13	kw
Power as 50%	6.5	kw
Power consumption 50%	**0.80**	**kwh**
Power consumption 100%	**1.61**	**kwh**

Electricity consumption calculation for 3D printing construction method

As mentioned above, the mathematical method was used to calculate the electricity consumption for the 3D printers. In the 3D printing construction method, electricity consumption for six machines was calculated: 3D printers, 3D printing concrete mixer and pump, concrete truck mixer, concrete truck pump, concrete hollow core slab making machine and wire strands machine. Moreover, for 3D printers, KUKA KR 120 R3900 ultra K was used for 3D printing the conventional villa. The KR 120 R3900 ultra K operates with a 120 kg payload, has six motors on each of its six axes and weighs approximately 1221 kg. 15.80 kW is the power rating of the motors when operating at full capacity. Usually, the robot works with 50% capacity, 7.90 kW. As for the 3D innovative villa, COBOD 2 gantry was used, which works with three axes and weighs 5023 kg. Also, 12.8 kW is the power rating of the motors when operating at full capacity and 6.4 kW when working at 50% capacity. Furthermore, to determine the time required for the 3D printing process, two aspects must be identified: firstly, the 3D printer speed; and secondly, the perimeter length of the pattern path or pattern line for the walls including all layers. In 3D printing, the length of the path or perimeter line is equal to the length of all the layers that make up the walls, which is equal to the perimeter of a single layer times the number of layers.

The length of the total path line for a 3D standard villa is 149,110.02 m, and for the 3D innovative construction method it is 124,574.41 m. It is possible to calculate the operation time by dividing the length of the perimeter by the speed of the 3D printer. The printing speed for both 3D standard and innovative construction methods had a 0.25 m/s setting (Besix 2019). Moreover, the printing layer high for both methods was 10 mm. Using the preceding equation, the electricity consumption for the 3D standard villa was 1308.9 kWh and 1083.87 kWh for the 3D innovative villa (Table 3-14) and (Table 3-15). For 3D printing, a concrete mixer and pump M-tec Duo mix Connect were used in this study as recommended by COBOD (2019). The electricity consumption of 3D printing concrete pumps in a 3D standard villa is 212.28 kWh (Table 3-16) and in a 3D printing innovative villa it is 164.58 kWh (Table 3-17).

Table 3-14 Calculation of Electric Consumption for 3D Printing Standard Villa KUKA Robot (KR 120 R3900 ultra K).

ENERGY CALCULATION		
All print length	149,110.02	m
Motion speed	0.25	m/sec
Total time	**9940.67**	min
Time as hour	165.68	hr
Power as 100%	15.80	kw
Power as 50%	7.90	kw
Power consumption 50%	**1308.9**	**kwh**
Power consumption 100%	**2617.7**	**kwh**

Table 3-15 Calculation of Electric Consumption for 3D Printing Innovative Villa COBOD 2.

ENERGY CALCULATION		
All print length	124,574.41	m
Motion speed	0.25	m/sec
Total time	**8304.96**	min
Time as hour	138.42	hr
Power as 100%	15.66	kw
Power as 50%	7.83	kw
Power consumption 50%	**1083.87**	**kwh**
Power consumption 100%	**2167.73**	**kwh**

Table 3-16 Calculation of Electric Consumption for 3D Printing Concrete Mixer and Pump for 3D Printing Standard Villa.

ENERGY CALCULATION		
Volume of concrete	54.147	m3
m3 to L	54147	L
Pump rate	22	L/m
Total time	2461.227273	min
Time as hour	41.02045455	hr
Power as 100%	10.35	kw
Power as 50%	5.175	kw
Power consumption 50%	**212.28**	**kwh**
Power consumption 100%	**424.56**	**kwh**

Table 3-17 Calculation of Electric Consumption for 3D Printing Concrete Mixer and Pump for 3D Printed Innovative Villa.

ENERGY CALCULATION		
Volume of concrete	41.98	m3
m3 to L	41980	L
Pump rate	22	L/m
Total time	1908.18	min
Time as hour	31.80	hr
Power as 100%	10.35	kw
Power as 50%	5.175	kw
Power consumption 50%	**164.58**	**kwh**
Power consumption 100%	**329.161**	**kwh**

The electricity consumption for the concrete truck mixer, concrete truck pump, concrete hollow core slab making machine and wire strands machine can be seen in (Table 3-18), (Table 3-19) , (Table 3-20) , and (Table 3-21) for a 3D printing standard villa and in (Table 3-22), (Table 3-23), (Table 3-24), and (Table 3-25)for a 3D printing Innovative villa.

Table 3-18 Calculation of Concrete Truck Mixer Electricity Consumption for 3D Printing Standard Villa.

ENERGY CALCULATION		
Concrete volume	229.3	m3
Motion speed	4	m3/min
Total time	57.33	min
Time as hour	0.96	hr
Power as 100%	17.50	kw
Power as 50%	8.75	kw
Power consumption 50%	**8.36**	**kwh**
Power consumption 100%	**16.72**	**kwh**

Table 3-19 Calculation of Concrete Pump Electricity Consumption for 3D Printing Standard villa.

ENERGY CALCULATION		
Concrete volume	229.3	m3
Motion speed	0.5	m3/min
Total time	458.60	min
Time as hour	7.64	hr
Power as 100%	260	kw
Power as 50%	130	kw
Power consumption 50%	**993.63**	**kwh**
Power consumption 100%	**1987.27**	**kwh**

Table 3-20 Calculation of Concrete Hollow Core Slab Making Machine Electricity Consumption for 3D Printing Standard Villa.

ENERGY CALCULATION		
Casting length	251.5	m3
Motion speed	1.85	m3/min
Total time	135.95	min
Time as hour	2.27	hr
Power as 100%	45	kw
Power as 50%	22.5	kw
Power consumption 50%	**50.98**	**kwh**
Power consumption 100%	**101.96**	**kwh**

Table 3-21 Calculation of Wire Strands Machine Electricity Consumption for 3D Printing Standard Villa.

ENERGY CALCULATION		
Concrete volume	251.5	m3
Motion speed	36	m3/min
Total time	6.99	min
Time as hour	0.12	hr
Power as 100%	13	kw
Power as 50%	6.5	kw
Power consumption 50%	**0.76**	**kwh**
Power consumption 100%	**1.51**	**kwh**

Table 3-22 Calculation of Concrete Truck Mixer Electricity Consumption for 3D Printing Innovative Villa.

ENERGY CALCULATION		
Concrete volume	164.45	m3
Motion speed	4	m3/min
Total time	41.11	min
Time as hour	0.96	hr
Power as 100%	17.50	kw
Power as 50%	8.75	kw
Power consumption 50%	**5.99**	**kwh**
Power consumption 100%	**11.99**	**kwh**

Table 3-23 Calculation of Concrete Pump Electricity Consumption for 3D Printing Innovative Villa.

ENERGY CALCULATION		
Concrete volume	164.45	m3
Motion speed	0.5	m3/min
Total time	328.90	min
Time as hour	5.48	hr
Power as 100%	260	kw
Power as 50%	130	kw
Power consumption 50%	**712.62**	**kwh**
Power consumption 100%	**1425.23**	**kwh**

Table 3-24 Calculation of Concrete Hollow Core Slab Making Machine Electricity Consumption for 3D Printing Innovative Villa.

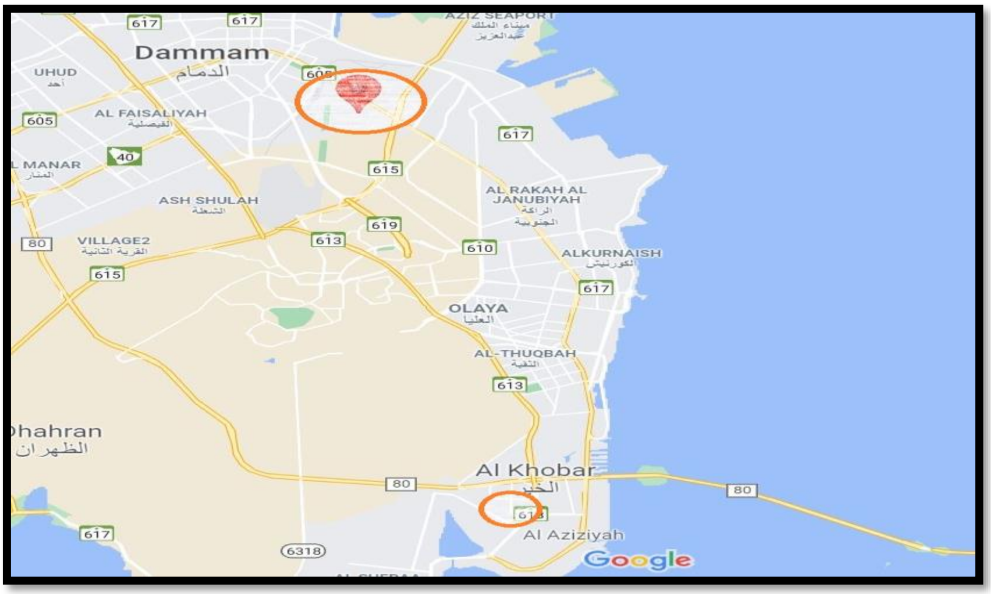
ENERGY CALCULATION		
Casting length	256.12	m3
Motion speed	1.85	m3/min
Total time	138.44	min
Time as hour	2.31	hr
Power as 100%	45	kw
Power as 50%	22.5	kw
Power consumption 50%	**51.91**	**kwh**
Power consumption 100%	**103.83**	**kwh**

Table 3-25 Calculation of Wire Strands Machine Electricity Consumption for 3D Printing Innovative Villa.

ENERGY CALCULATION		
Concrete volume	256.12	m3
Motion speed	36	m3/min
Total time	7.11	min
Time as hour	0.12	hr
Power as 100%	13	kw
Power as 50%	6.5	kw
Power consumption 50%	**0.77**	**kwh**
Power consumption 100%	**1.54**	**kwh**

Transportation Data

The transportation data for this study was not assumed according to previous studies but according to the actual distance from the factories to the construction site. The information was obtained from the architecture firm responsible for constructing the project. For the concrete and concrete masonry units (CMU), the distance was 26 km, and for all other materials, it was 10 km. An assumption of 26 km was made, as shown in (Figure3-12), for the transport of the 3D printer.



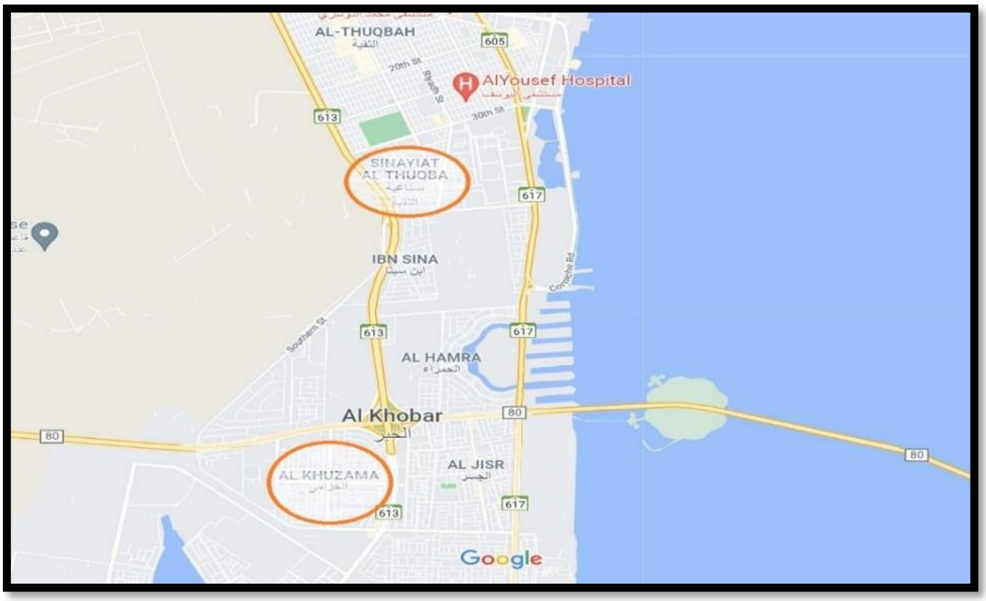


Figure 3-12 Google Map for Material Transportation.

LCA databases and software

As mentioned earlier in Table 1, the LCA process might make use of many databases and software application. The Ecoinvent v3.1 database was employed for research and assessments since it is a compliant data source, as advised in ISO 14040 and 14044.Additionally, this research utilised SimaPro 9.0.0.35 software (PRe 2019), which provides multiple methods such as CML 2001, EDIP 97, IMPACT 2002+, ReCiPe and multiple databases such as USLCI, Ecoinvent and ELCD (Khasreen et al. 2009). Appendix A shows a screen of SimaPro in use.

Life cycle impact method (LCIA)

Following the (LCI) phase, life cycle impact method (LCIA) finds and coverts the related emissions into damage indicators that demonstrate the environmental impact (Lasvaux et al. 2016). Like the LCI phase, the selected impact categories and methods are bounded by the Goal and Scope Definition (Goedkoop et al. 2016). Furthermore, LCIA reveals the consumption of land use and water resources and the environmental impact of the emitted substances (i.e., CO2, CO, CH4, etc.) (Finnveden et al. 2009). LCIA categorises these impacts as, the midpoint impact and endpoint impact (Goedkoop et al. 2016). The midpoint and endpoint consist of optional components (i.e., normalisation, grouping, weighting) and mandatory components (i.e., classification and characterisation) (Goedkoop et al. 2016). Choosing the endpoints impacts should be done carefully because endpoint methods include additional uncertainty (Kägi et al. 2015).

Classification

During this stage, two steps are identified. The first one is the selection of impact categories, in which it establishes the related information of the used energy and resources, and this selection should be guided by the goal of the study (Goedkoop et al. 2016; Gonçalves et al. 2013; Lopes et al. 2002; Da Silva Vieira et al. 2010; ISO 14040 2006) stated the commune used environmental impact which includes:

Global warming potential (GWP)

"*When speaking of global warming today, one usually refers to those emissions released from mankind which enhances the natural occurring global warming, which in the long run raises the average temperature on the earth. GWP is a measure of how much a unit mass of gas contributes to global warming, measured in kg CO2 equivalents. Other important gases besides CO2 are methane (CH4) and nitrous oxide (N2O)*" (Dahlgren et al. 2015).

Photochemical Oxidant Formation Potential (POFP)

"*Photochemical ozone creation potential is also known as ground-level smog, photochemical smog, or summer smog. It is formed within the troposphere from a variety of chemicals including NOx, CO, CH4, and other volatile organic compounds (VOCs) in the presence of high temperatures and sunlight. It has negative impacts on human health and the environment and is expressed as C_2H_4 equivalents*" (Čuček et al. 2015).

Eutrophication Potential (EP)

"*Eutrophication potential leads to an increase in aquatic plant growth attributable of nutrients left by over-fertilization of water and soil, such as nitrogen and phosphorus. Nutrient enrichment may cause fish death, declining water quality,* *decreased biodiversity, and foul odours and tastes. It is expressed in PO_4^{3-} equivalents.*" (Čuček et al. 2015).

Ozone Depletion Potential (ODP)

"*Refers to the thinning of the stratospheric ozone layer as a result of anthropogenic emissions. This causes a greater fraction of solar UV-B radiation to reach the earth's surface, with potentially harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials*" (Fava 1993).

Acidification Potential (AP)

"*Acidification means that substances with low pH are emitted to water and soils to such degree that they don't have any chance to become naturally neutralized. Sulphur dioxide (SO2) and nitrogen oxides (NOX) are important contributors which form sulphuric and nitric acid in contact with water in the atmosphere, called acid rain. This causes corrosion damages on buildings etc. which results in high costs for the society. Also, acidification of lakes can lead to death of certain species living there and acidification of soil can lead to nutrient leaching and decreased vegetation growth*" (Dahlgren et al. 2015).

Toxicity potential

Eco-toxicity: "*This impact category covers the impacts of toxic substances on aquatic, terrestrial and sediment ecosystems. The area of protection is the natural environment (and natural resources). This impact has subcategories, like: Freshwater aquatic, marine aquatic and terrestrial ecotoxicity*" (Fava 1993).

Human toxicity: "*Is a calculated index that reflects the potential harm of a unit of chemical released into the environment. It is based on both the inherent toxicity of a compound and its potential dose. It is used to weigh emissions inventoried as part of a life-cycle assessment*" (Fava 1993).

The second step is the selection of the impact assessment methods, such as EDIP, EPS 2000, CML 2007 and ReCipe (Goedkoop et al. 2016). (Table 3-26) shows a summary of the usually employed methods in the field of construction around the world. Moreover, the majority of LCA specialists prefer working with the existing methods to working from scratch (Goedkoop et al. 2016; ISO 14040 2006). Also, using more than one method of assessment could lead to different findings (Frischknecht et al. 2016). Owsianiak et al. (2014) evaluated their findings using ReciPe 2008 and EDIP, 2002+, and the results of the comparison showed significant differences.

Table 3-26 a Summary of the Usually Employed Methods in the Field of Construction Around the World. Sources Adopted and Revised from Cavalett et al. (2013), Gonçalves et al. (2013) and Park et al. (2020).

Environmental Impact	Method	Impact Categories	Midpoint/ Endpoint
Global warming	EPS 2000	…………	Midpoint
	IMPACT 2002+	Global warming	Midpoint/Endpoint
	ReCiPe	Climate change, climate change impact on human health, climate change ecosystems	Midpoint/Endpoint
	Eco-indicator 99	Climate change	Endpoint
	CML 2007	Global warming	Midpoint
	TRACI	Global warming	Midpoint
	EDIP	Global warming	Midpoint
Photo-oxidation formation	EPS 2000	…………	Midpoint
	IMPACT 2002+	Respiratory organics	Midpoint/Endpoint
	ReCiPe	Photochemical oxidant formation formation	Midpoint/Endpoint
	Eco-indicator 99	Respiratory organics	Endpoint
	CML 2007	Photochemical oxidation	Midpoint
	TRACI	Human respiratory, photochemical smog	Midpoint
	EDIP	Photochemical ozone formation	Midpoint

Environmental Impact	Method	Impact Categories	Midpoint/ Endpoint
Global warming	EPS 2000	…………	Midpoint
	IMPACT 2002+	Global warming	Midpoint/Endpoint
	ReCiPe	Climate change, climate change impact on human health, climate change ecosystems	Midpoint/Endpoint
	Eco-indicator 99	Climate change	Endpoint
	CML 2007	Global warming	Midpoint
	TRACI	Global warming	Midpoint
	EDIP	Global warming	Midpoint
Eutrophication	EPS 2000	…………	Midpoint
	IMPACT 2002+	Terrestrial acid/nutri, aquatic eutrophication	Midpoint/Endpoint
	ReCiPe	Marine eutrophication, freshwater eutrophication	Midpoint/Endpoint
	Eco-indicator 99	Acidification/Eutrophication	Endpoint
	CML 2007	Eutrophication	Midpoint
	TRACI	Eutrophication	Midpoint
	EDIP	Eutrophication	Midpoint
Ozone depletion	EPS 2000	…………	Midpoint
	IMPACT 2002+	Ozone layer depletion depletion	Midpoint/Endpoint

Environmental Impact	Method	Impact Categories	Midpoint/ Endpoint
Global warming	EPS 2000	…………	Midpoint
	IMPACT 2002+	Global warming	Midpoint/Endpoint
	ReCiPe	Climate change, climate change impact on human health, climate change ecosystems	Midpoint/Endpoint
	Eco-indicator 99	Climate change	Endpoint
	CML 2007	Global warming	Midpoint
	TRACI	Global warming	Midpoint
	EDIP	Global warming	Midpoint
	ReCiPe	Stratospheric ozone depletion	Midpoint/Endpoint
	Eco-indicator 99	Ozone layer depletion	Endpoint
	CML 2007	Ozone layer depletion	Midpoint
	TRACI	Ozone depletion	Midpoint
	EDIP	Ozone depletion	Midpoint
Acidification	EPS 2000	Soil acidification	Midpoint
	IMPACT 2002+	Aquatic acidification, terrestrial acid/nutri	Midpoint/Endpoint
	ReCiPe	Terrestrial acidification	Midpoint/Endpoint
	Eco-indicator 99	Acidification/Eutrophication	Endpoint
	CML 2007	Acidification	Midpoint

Environmental Impact	Method	Impact Categories	Midpoint/ Endpoint
Global warming	EPS 2000	…………	Midpoint
	IMPACT 2002+	Global warming	Midpoint/Endpoint
	ReCiPe	Climate change, climate change impact on human health, climate change ecosystems	Midpoint/Endpoint
	Eco-indicator 99	Climate change	Endpoint
	CML 2007	Global warming	Midpoint
	TRACI	Global warming	Midpoint
	EDIP	Global warming	Midpoint
	TRACI	Acidification	Midpoint
	EDIP	Acidification	Midpoint
Toxicity	EPS 2000	Life expectancy, severe morbidity, morbidity, severe nuisance	Midpoint
	IMPACT 2002+	Aquatic ecotoxicity, terrestrial ecotoxicity, carcinogens, non-carcinogens	Midpoint/Endpoint
	ReCiPe	Terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity	Midpoint/Endpoint
	Eco-indicator 99	Ecotoxicity, carcinogens	Endpoint
	CML 2007	Freshwater aquatic ecotoxicity, terrestrial ecotoxicity, marine aquatic ecotoxicity, human toxicity	Midpoint

Environmental Impact	Method	Impact Categories	Midpoint/ Endpoint
Global warming	EPS 2000	…………	Midpoint
	IMPACT 2002+	Global warming	Midpoint/Endpoint
	ReCiPe	Climate change, climate change impact on human health, climate change ecosystems	Midpoint/Endpoint
	Eco-indicator 99	Climate change	Endpoint
	CML 2007	Global warming	Midpoint
	TRACI	Global warming	Midpoint
	EDIP	Global warming	Midpoint
	TRACI	Ecotoxicity, carcinogens, non-carcinogens	Midpoint
	EDIP	Ecotoxicity, persistent toxicity, human toxicity, hazardous waste, bulk waste, slag and ashes	Midpoint

Characterisation

ISO 14040 (2006) describes the characterisation stage as the stage in which the calculation of the LCI findings is transferred into units that are common and gathered to the same impact category. For example, 3 kg of CH_4 and 5 kg of CO_2 yield 68 kg CO_2 equivalent, causing climate change (ISO 14040 2006).

Normalisation

The normalisation stage shows how the size of an impact category's results is calculated in relation to the reference data (ISO 14040 2006). The reference information could be for a specific area, product or person (Bare 2014). Normalisation shows the damage caused by the released substance on the ecosystem and human health and the resulting reduction of resources (Bare 2014).

Grouping

The grouping stage is the process where the impact categories are collected inside several sets including ranking and sorting (ISO 14040 2006). The grouping in LCIA data is done in two ways (BSI 2018):

a- Distinguishing impact categories on a hierarchy arrangement, like low to high.

b- Sorting impact categories on a nominal ground, for instance, local spatial scales and global regional or inputs and outputs.

Weighting

The weighting stage is when the impact categories are aggregated and converted using numerical factors (BSI 2018). The weighting process is built on value choices not on a scientific perspective (BSI 2018); therefore, the weighting factor is different from one country to another (Kägi et al. 2015; ISO 14040 2006).

The impact method's selection is considered subjective but should be consistent with the ISO recommendations for the LCIA method (Blengini and Di Carlo 2010).

The ReCiPe Midpoint (H) v1.03 method was applied in this research since it provided a wide variety of environmental categories and was employed in the majority of scientific studies on LCA (Agustí-juan et al. 2017; Huijbregts et al. 2017). According to the United Nations Environment Programme's (UNEP/SETAC2016) recommendations, this study implemented the Available Water Remaining (AWARE) method for water use analysis. The ReCiPe Midpoint impact method has 18 categories (Huijbregts 2016), as shown in (Figure 3-13), nonetheless, this work focused on the impact categories that cumulatively include no less than 80% of the overall environmental impacts, without toxicity associated impact categories (European-Commission 2017). Moreover, as advised by the Product Environmental Footprint Category Rules (PEFCR) Guidance, the seven most relevant impact categories are: 1) global warming; 2) fine particulate matter formation; 3) stratospheric ozone depletion; 4) land use; 5) marine eutrophication; 6) water use (AWARE) and 7) mineral resource scarcity. For this study, the most recent weighting and normalisation factors were taken from the European Commission Platform on Life Cycle Assessment (European-Commission 2017; Sala et al. 2018).

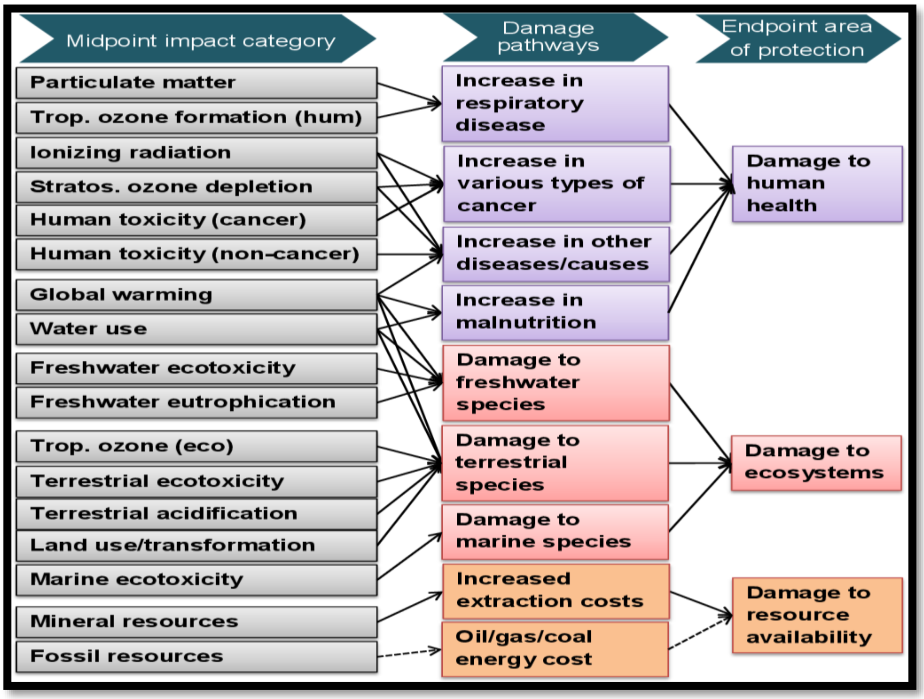


Figure 3-13 An Overview of the Impact Categories Covered by the ReCiPe Method.

Interpretation

Interpretation is the last stage in the LCA methodology, and it includes aggregating all LCA results and organising them in a proper context (Ochsendorf et al. 2011; Skone 2000). To better interpret the LCA results, BSI (2018) provided three steps:

a- To identify the main concerns depending on the outcomes of LCI and LCIA (i.e., the goal and scope of the study, functional units, system boundary, data availability, data collection, limitations, and assumptions of the study).

b- To measure the consistency, sensitivity, and completeness of the study. A consistency test is done by ensuring that all data, assumptions, and methods are constant during the study, otherwise the outcome of the study may vary. A sensitivity test is done by ensuring that the chosen data and method are related to the LCA study. A completeness test is done by ensuring that the collected data for the study is adequate in order to achieve significant conclusions.

c- To draw conclusions, limitations, and present recommendations.

Critical Review

To guarantee the quality of the research work complies with ISO 14040, this study will be assessed by an external and internal examiner, and the methodology is published in a high impact factor journal (Journal of Cleaner Production).

3.3.2. Part 2: A Cost Analysis Study of Conventional and 3D Printing Technology Construction Methods

The scope of the economic analysis for this study will be focusing only on the cost analysis of 3D printing technology construction methods compared to conventional construction methods. The researcher calculated, compared, and analysed the material and construction costs. The economic analysis for this study was done on the internal and external walls for the four scenarios without the finishing phase. Furthermore, the roof and the foundation cost were not included in this study because constructing them is relatively similar. The analysis will be done in two phases: the first phase is the materials cost. In this phase the data were obtained from The General Authority for Statistics (GaStat 2020), Saudi Contractors Authority (SCA 2020), Madar Building Materials (MADAR 2020), National Water Company (NWC) (NWC 2020), Sika Saudi Arabia Co. Ltd (SiKa 2020) and Al Rashed Cement. The second phase is the construction cost where the data was gained from The General Authority for Statistics (al Rashed 2020), Aramco (Aramco 2020), and Saudi Electricity Company (SEC 2018).

For the number of labourers and construction time, the information for the conventional villa was obtained from the architectural firm that designed and constructed the project. For the precast villa, the information was received from engineers who owned and worked in precast factories. Moreover, the information for standard and innovative 3D printed villas was gained from observing other 3D printed projects in the literature. The construction time for 3D printing methods was calculated by the researcher and the wages for engineers and labourers were obtained from the employment and wages survey (GaStat 2017).

3.3.3. Part 3: Analytic Study of Construction Industry's Perception of 3D Printing Construction Method

Diffusion Innovation Theory

Diffusion is commonly understood as the procedure through which innovations are distributed among public in a social system over time and through certain channels (Rogers 1983). In 1983, (DIT) was initiated by Rogers, but then again, in 1995 and 2003, this theory was further developed by him. Moreover, In the context of the choice to accept and apply innovation, Rogers utilized adoption. Rogers described the terms innovation, diffusion and communication as follows: Innovation is an object, practice, or a concept that an individual recognises. Diffusion is the procedure through which an invention is transmitted to the general public over time through specific channels. Communication is a method that includes the sharing and creating information to achieve a common perception among the public. According to this theory, an individual collects information about innovation to create a perception. Then, these observations provide the drivers that affect his/her decision to accept or refuse the innovation (Moore and Benbasat 1991).

Rogers (1983) declares that there are four major factors affect the spread of a new idea amongst a population, including innovation, communication channels, time, and social system. Innovation is defined as "an idea, practice, or object that is perceived as new by an individual or other unit of adoption." Moreover, Roger (1983) describes communication channels as "the means by which messages get from one individual to another." Communication channels are the methods throughout how members are generating and sharing knowledge to achieve mutual awareness. Also, time is clearly identified as an "innovation-decision period which is the length of time it takes for one to decide on adopting an innovation". Finally, a social system is explained by Roger (1983) as a "set of interrelated units that are engaged in joint problem solving to accomplish a common goal." Some topics engage connections between the diffusion process and the social system. These topics consist of exactly in what way the social structure affects diffusion, the impact of customs and standards on diffusion, the positions of change agents and opinion leaders, the kinds of innovation decisions done by people and finally, the consequences of innovation.

The innovation-decision procedure, throughout which an individual chooses to adopt or refuse an innovation, is divided into five major phases as shown in (Figure 3-14). **Knowledge** is considered the first stage in which the individual is subjected to innovation and recognises the function (Rogers 1983). During this phase, the individuals are delivered with knowledge about an innovation. Then, the innovation is presented to potential individuals to generate consciousness about its presence and provide them with essential knowledge about how to utilise it correctly. Understanding can be accomplished through various media devices; experience can be accomplished from change agents and official training, or teaching presented by the organisation. The second phase of this procedure is **persuasion.** During this phase, the individual is motivated by looking for innovation (Rogers 1983), wherein individuals begin to collect reliable data from numerous resources regarding the innovation to develop positive or negative beliefs about it. These beliefs are supposed to guide individuals to change their upcoming behaviours.

Afterwards, according to Rogers (1983), the individual participates and makes a decision if they should accept or refuse the innovation in the **decision** phase. The decision phase, in which she/he evaluates the innovation, is considered the most challenging phase. During this phase, the individual assesses the decision's benefits and weaknesses to determine if they should accept or refuse the innovation. Rejecting the innovation can be done in two ways. The first way is active rejection, in which the individual chooses not to utilise the innovation after testing. The second way is using passive rejection, wherein the individual refuses the idea of using innovations, even on a trial basis. According to Rogers (1983), the next phase is **implementation,** wherein he/she adopts the innovation. The individual will start to utilise the innovation immediately after she/he decides to accept the innovation. Lastly, **confirmation** is the final phase. According to Rogers (1983), through this phase, the individual pursues to reinforce the decision that she/he made to adopt the earlier decision that the individual made, which might be changed if subjected to a clashing point on the innovation notion. Moreover, he/she emphasises that the decision to accept the innovation depends on her/his initial usage experiences. To conclude, one phase might or might not direct to the following phase depending on how positively the determination of the previous phase (Rogers 1983).

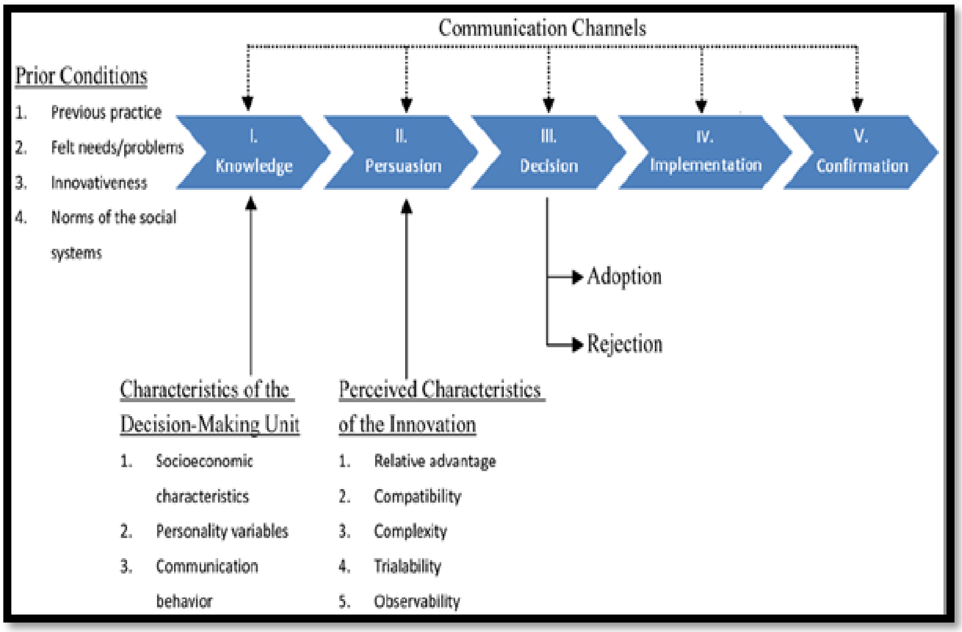


Figure 3-14 Conceptual Framework of (Rogers 1983) Model.

Several attributes of innovation are identified as they were recognised as assisting (DOI) and suggested five attributes that perform a vital part in an individual's opinions to the adoption of a certain innovation (Rogers 1983). Also, the rate of adoption of an innovation is the relative speed at which people in a certain social system adopt it. This is usually measured by the number of people who adopt an innovation in a certain time frame (Rogers 1983). The speed at which a social system adopts new ideas is called adoption rate. Moreover, Rogers emphasises that the rate of adoption for an innovation essentially relies on five characteristics of innovation: Complexity (COMX), Relative Advantage (RADV), Trialability (TRB), Observability (OBS) and Compatibility (COMP). The definition of each attribute is presented in (Table 3-27). These attributes might be a contributing factor in the adoption rate that was noticed by the adapter. Furthermore, Rogers (1983) explains that the shape of the decision procedure could also influence the rate of adoption.

Table 3-27 The Five Attributes in DOI (Rogers 1983).

Attribute	Definition
Relative advantage	"The degree to which an innovation is perceived as better than the idea it supersedes"
Compatibility	"The degree to which an innovation is perceived as being consistent with the existing values, past experience and needs of potential adopters"
Complexity	"The degree to which an innovation is perceived as difficult to understand and use"
Trialability	"The degree to which an innovation may be experimented with on a limited basis"
Observability	"The degree to which the results of an innovation are visible to others"

Crucially, the DOI theory recognises that the adoption of innovation does not occur simultaneously along with all individuals and parts of a social system. Instead, several people can adopt innovations faster than the other members (Rogers 1983). There are five main groups that adopters of innovation could be classified to: Innovators, Early Adopters, Early Majority, Late Majority and Laggards (Figure 3-15).

Innovators (Venturesome), Observers have noted that innovators are obsessed with risk-taking. Innovators are eager to test out new concepts. This curiosity frequently leads them away from their local peer networks and into new cosmopolite social ties.

Early Adopters (Respectable) are seen as a group of a local social systems where they live. Early Adopters are the opinion leaders whose beliefs and judgments, experiences and steps motivate the early majority to adopt. Early adopters can serve as a source of information and help for possible adopters.

Early Majority (Deliberate) are simply explained as the adoption of new concepts by a normal individual of a social system. In comparison to innovators and early adopters, their decision-making process for innovations takes a while.

Late Majority (Sceptical) is expressed as while the normal individual of a social system has already been engaged with new ideas, they might adopt it. Also, the Late Majority are more likely to be uncertain. They would like to observe that the innovation is performing well amongst the early majority before adopting it.

Laggards (Traditional) are viewed as the last group on the adoption of an innovation. The individual might cooperate with others who have relatively traditional beliefs.

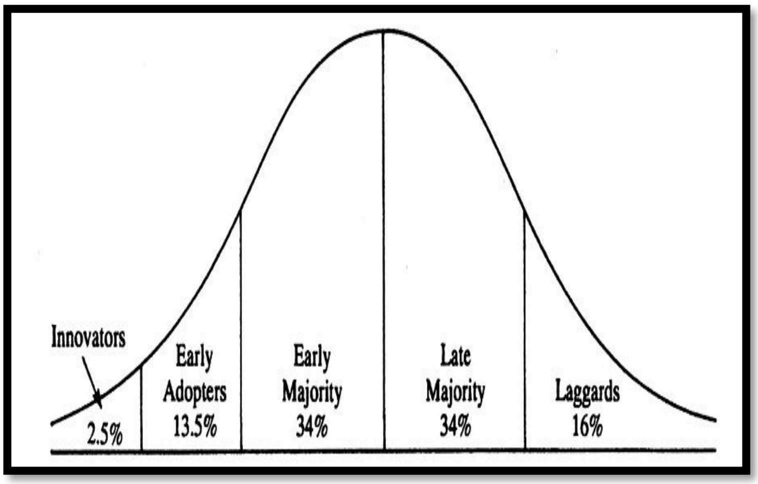


Figure 3-15 The Diffusion of Innovations- Five Groups (Rogers 1983).

Limitations of DOI Theory

The DOI theory undergoes various limitations even though it has several practical implications. Botha and Atkins (2005) reveal that DOI does not consider the possibility that people will refuse an innovation even if they understand it completely. Because of its pro-innovation bias, DOI is technology-driven (Karch et al. 2016). Pro-innovation bias indicates that each member of a social system must adopt innovations, and that the adoption must occur immediately. Distinguishing the very important aspects that impact the diffusion of innovations is difficult. According to MacVaugh and Schiavone (2010), that happens since the diffusion process can be affected by the interaction between several contextual aspects of adopters, for instance, social and technological situations.

Moreover, the truth of the knowledge application or use in the diffusion of innovations is more difficult and problematic by contrasting simple adoption (replication) versus reinvention (adaptation) (Nutley et al. 2002). Four essential elements of adoption should be considered to suggest a better reason for adopting innovations. These elements consist of socio-economic influences, innovation characteristics, organisational characteristics, and the characteristics of the adopters.

However, Wisdom et al. (2014) points out that the combination of the crucial ideas of these four fundamental features all together may remain a difficult and more tough task to fulfil.

According to Botha and Atkins (2005), it does not bear in mind that diffusion and adoption may undergo failure because it was not a good idea to start with. It associates the most recent technologies with progress. In that way, it does not take into account other alternatives. Furthermore, there is a great demand to use various theoretic lenses, together with the diffusion theory and a view to providing a better insight of the main aspects affecting the spreading of new innovations (Lyytinen and Damsgaard 2001).

Reasons for Choosing the Selected Theory

(DOI) produced by Rogers (1983) is a commonly accepted framework for evaluating the adoption of new technologies. Previous studies in Chapter 2 mentioned that DOI has been used to study the adoption of 3D printing technology as a single theory or in combination with other theories for instance the (TPB), (TAM), and (UTAUT). The rationale behind choosing DOI for this study is that the DOI attributes align with the aim and objectives of the study. Additionally, Marak et al. (2019) suggest that DOI explains the procedure of adopting the technology, for example, understanding the technology, the interest of adopting the technology, the intention of adopting the technology and finally, adopting the technology. DOI presents a theoretical foundation to discuss the adoption of new technologies globally, not only at an individual and organisational level (Taherdoost 2018). Furthermore, DOI expresses organisational factors, best practice factors and environmental factors that influence the decision of adoption (Ungan 2004). DOI is considered to be one of the highly common theories used in the studies of 3D printing technology (Marak et al. 2019; Chatzoglou and Michailidou 2019; Oettmeier and Hofmann 2017).

Questionnaire design

Questionnaires are the preferred collection method more than case studies and interviews (Saunders et al. 2012). When researchers aim to gather thoughts and opinions from a big sample at a reasonably low cost, they develop a questionnaire that includes a list of structured and pre-tested questions (Collins and Hussey 2009). Furthermore, Huang (2006) suggested that surveys are the most common way of data collecting, while emphasising that surveys attempt to investigate reliable estimates of the frequency of relevant variables. The development and adaptation of the questionnaire for this study were from previous studies on the adoption of 3D printing technology in different construction and manufacturing areas. The first section of the questionnaire was an introduction page which introduced the topic and the objectives of the conducted research. The second section was a consent form ensuring the confidentiality of participants information. The third section was about the demographic profile of participants.

The demographic profile was based on the General Authority for Statistics in Saudi Arabia. The fourth section introduced the used theory in the study, which is the diffusion of Innovations theory (DIT). After that, each attribute's relative advantage, complexity, compatibility, observability and trialability had a separate section to be answered. The last section of the questionnaire included thanking the participants and the contact information of the researcher and the supervisor. The study used a five-point Likert scale rank from '1 =strongly disagree, 2= disagree, 3= Neutral, 4= agree, 5 = strongly agree'. Researchers recommended a five-point scale to increase the response quality and the response rate and reduce frustration (Bakus and Mangold 1992; Finstad 2010). The questionnaire is provided in Appendix B. (Table 3-28) presents the development of the questionnaire.

Table 3-28 Questionnaire Development.

Attribute	Items	Sources
Relative Advantage	3D printing technology reduces the construction cost of a building.	(Geneidy et al. 2019), (Marak et al. 2019), (Chatzoglou and Michailidou 2019), (Pimpley 2019), (Oettmeier and Hofmann 2017), (Wu et al. 2018), (Yeh and Chen 2018).
	3D printing technology reduces the construction time of a building.	(Chatzoglou and Michailidou 2019), (Geneidy et al. 2019), (Marak et al. 2019), (Olsson et al. 2019), (Pimpley 2019), (Wu et al. 2018)
	3D printing technology reduces construction material waste.	(Pimpley 2019), (Oettmeier and Hofmann 2017).
	3D printing technology can produce more complex shapes than other construction methods.	(Pimpley 2019).
	3D printing technology lowers overall construction life cycle environmental impacts.	(Pimpley 2019), (Wu et al. 2018), (Yeh and Chen 2018).
	3D printing technology improves the quality of construction.	(Chatzoglou and Michailidou 2019), (Marak et al. 2019), (Wu et al. 2018).
	3D printing technology enhances construction productivity.	(Chatzoglou and Michailidou 2019), (Marak et al. 2019), (Marak et al. 2019).
	3D printing technology improves the functionality of the finished building.	(Oettmeier and Hofmann 2017).
Complexity (Ease of Use)	3D printing technology is easy to understand and use.	(Chatzoglou and Michailidou 2019), (Marak et al. 2019),

Attribute	Items	Sources
		(Pimpley 2019), (Oettmeier and Hofmann 2017).
	Adopting 3D printing technology improves collaboration among architects, engineers, consultants and contractors.	(Pimpley 2019).
	Implementing 3D printing technology is a simple process.	(Marak et al. 2019), (Oettmeier and Hofmann 2017).
	Setting up 3D printing technology is clear and straightforward.	(Marak et al. 2019).
	Finding employees who can operate 3D printers is easy.	(Marak et al. 2019), (Oettmeier and Hofmann 2017), (Geneidy et al. 2019).
	It is easy to find experts to discuss and share their experience and knowledge of 3D printing technology.	(Geneidy et al. 2019).
Compatibility	3D printing technology is consistent with the needs of my workplace.	(Chatzoglou and Michailidou 2019), (Marak et al. 2019), (Oettmeier and Hofmann 2017).
	My workplace has already investigated 3D printing technology.	(Marak et al. 2019).
	My workplace intents to provide seminars and workshops on 3D printing technology.	(Geneidy et al. 2019).
	The materials used in 3D printing technology are compatible with conventional construction.	(Pimpley 2019).
	3D printing technology is compatible with a construction site environment.	(Pimpley 2019).

Attribute	Items	Sources
	3D printing technology has the flexibility to print various sizes of objects for different construction needs.	(Pimpley 2019).
Observability	I have observed how 3D Printing technology is faster than traditional construction.	(Marak et al. 2019).
	I have observed how 3D Printing technology is more effective than traditional construction.	(Pimpley 2019), (Marak et al. 2019).
	I have observed how 3D Printing technology gives greater control over work quality parameters.	(Chatzoglou and Michailidou 2019), (Marak et al. 2019), (Wu et al. 2018).
	I have observed how 3D printing technology is more economical than conventional construction methods.	(Marak et al. 2019).
	I have observed that 3D printing technology produces more aesthetically pleasing results.	(Marak et al. 2019).
	I have observed that 3D printing technology offers a competitive advantage to a company.	(Marak et al. 2019).
Trialability	Before deciding whether to use 3D Printing technology in construction or not, my workplace would need to try the process and technology.	(Marak et al. 2019).
	My workplace would adopt 3D printing technology only if other companies or firms started using it.	(Geneidy et al. 2019).

Attribute	Items	Sources
	The ability to try 3D printing technology before adoption provides the possibility of risk reduction.	(Marak et al. 2019).
	3D printing technology building codes and regulations should be accredited before trying the technology	(Geneidy et al. 2019), (Marak et al. 2019), (Wu et al. 2018).
	My firm will experiment with 3D printing technology in the next 5 years.	(Marak et al. 2019).
	There are many hurdles to overcome before my workplace can experiment with 3D printing technology.	(Marak et al. 2019), (Wu et al. 2018).

Hypothesis development

A hypothesis is recognised as the researcher's prediction about the probable results of the relationship between variables (Creswell 2014). As previously previewed in Chapter 2, the development of 3D printing technology in construction is yet at an initial phase. There is not enough examination to be aware of users' acceptance of 3D printing technology in their workplace. To apply 3D printing technology in developing countries, a research gap was found in previous studies on the acceptance of 3D printing technology in construction. Also, it was discovered that several scholars had indicated numerous hypotheses stand on various models to investigate the acceptance of 3D printing technology. This research study has suggested some hypotheses to investigate the professional attitude and willingness towards adopting the 3D printing construction method as a new construction method in Saudi Arabia. These hypotheses were developed from the findings of previous studies in the literature review:

Relative Advantage

Hypothesis One: Relative advantage will have a significant positive effect on 3D printing technology adoption.

- Complexity (Ease to use):

Hypothesis Two: Complexity will have a significant positive effect on 3D printing technology adoption.

- Compatibility:

Hypothesis Three: Compatibility will have a significant positive effect on 3D printing technology adoption.

- Observability:

Hypothesis Four: Observability will have a significant positive effect on 3D printing technology adoption.

- Trialability:

Hypothesis Five: Trialability will have a significant positive effect on 3D printing technology adoption.

Questionnaire Translation

Although many architects and civil engineers in Saudi Arabia can speak and understand English from school, formal education or workplace, English is not considered the official spoken language in the country. Therefore, there was a need to translate the questionnaire from English to Arabic. The English version of the questionnaire was interpreted into Arabic language by the researcher, which Arabic is his first language, and then was validated through Al Thumali Translation Office, which is a certified translation office. The translation of the questionnaire can be found in Appendix B.

Pilot study

A pilot study can be described as a data collection testing tool. (Naoum 2012). Pilot testing is an instrument that will assure that participants will not face any difficulties in responding to the questions after testing it, and hence, it will work good in data collection in a full-scale (Saunders et al. 2012; Bryman and Bell 2015). Moreover, according to Robson (2011), a pilot study should be, if possible, the first stage of any data collection. Testing the questionnaire before proceeding to the data collection phase is considered to be an important step, as such piloting allows the researcher to identify and notice any deficiencies and weaknesses in the proposed content (Saunders et al. 2012). By doing that, pilot testing will allow the researcher to make adjustments and amendments to the proposed testing (Saunders et al. 2012). For this study, the researcher sent both the Arabic and English copies of the questionnaire to 15 architects and civil engineers from the construction industry in Saudi Arabia to receive their feedback on the questionnaire. The number was chosen according to the recommendation of Isaac and Michael (1995) and Putri (2012). They suggested that the sample size should be from 10 to 30, while van Belle (2002) recommended that the sample size should not be less than 12. First, the participants were asked to fill out the questionnaire and provide feedback on any problems, such as the questions' length, language, and clarity. After the pilot testing, it was found that there were no significant issues regarding the clarity of the questionnaire. Moreover, the participants spent about 5-7 minutes to answer the questionnaire. Some respondents suggested that the questionnaire should be shorter, and based on these recommendations, a few questions were taken out of the questionnaire.

Validity and Reliability

- Validity

Validity is expressed by Hair et al. (2010) as “the degree to which a measure accurately represents what it is supposed to.” Any instrument will confirm validity if it measures what it was aimed to measure (Black 1993). There are several different validity tests available to verify the reliability of a data collecting technique, including content validity, concurrent validity, construct validity, and predictive validity. The content validity test is the one that researchers employ the most frequently, including predictive validity, concurrent validity, content validity and construct validity; the most typical one being used by researchers is content validity (Cronbach and Meehl 2017). This type of test evaluates the level whereby the instrument elements' content suitably and broadly reflects the measured content. Sekaran (2003) and Saunders et al. (2012) emphasise that content validity indicates the degree of suitability with which the research instrument includes all parts of the proposed research ideas. To utilise a given concept, content validity proves that the measure for a component is sufficient, representative, and relevant (Sekaran and Bougie 2013).

To enhance the content validity of a questionnaire, various actions can be taken: first, the research topic should be thoroughly defined through the examination of related literature. Then, a group of experts should be contacted to examine the questions. Finally, the question will be sent to others to give their comments and suggestions (Saunders et al. 2012).

The following steps were done to guarantee the validity of the questionnaire:

1- The questions were modified from appropriate literature and related published papers in journals and conferences.
2- The questionnaire was evaluated through the judgement of both an expert and a supervisor.
3- Since the questionnaire was conducted in Arabic and English, the questionnaire was validated through a certified translation office to ensure there were no significant differences between the original Arabic version and the English one.
4- A pilot study was done with 15 participants to investigate any potential problems and obstacles faced while completing the questions. When formulating the final version of the questionnaire, the comments from the participants regarding time, clarity of language, instructions and questions order were taken under consideration.

- Reliability

Reliability is a measurement instrument's consistency, generating accurately and has stable responses over time (Pallant 2013; Saunders et al. 2012). Frequently, quite a few reliability tests are used to verify the consistency of instrument production. Most researchers use the inter-item consistency reliability test to determine internal consistency. To measure the interitem consistency reliability, Cronbach's alpha coefficient is believed to be the common test (Saunders et al. 2012). In order to achieve a reliable interterm, the result of the test must be closer to 1 (Pallant 2013). The coefficients for all attributes were 0.882 and ranged between 0.818 except for Trialability which had 0.646, which are all above the value of 0.6, which is believed an extremely reliable and suitable index (Nunnally and Bernstein 1994; Pallant 2013). This implies that all items in the attributes are sufficiently reliable measures. (Table 3-29) presents Cronbach's Alpha test.

Table 3-29 Cronbach's Alpha Test for Reliability.

Attributes	No. of Item	Mean	Standard Deviation	Cronbach's Alpha
Relative Advantage	8	3.797	0.289	0.767
Complexity	6	2.959	0.484	0.816
Compatibility	6	2.958	0.439	0.804
Observability	6	3.668	0.239	0.818
Trialability	6	3.891	0.451	0.646

Questionnaire Sampling Size

Frankfort-Nachmias and Nachmias (1996) reveal that sample size is the subgroup part of a larger group that derived from a population. For this study, the population size was driven from the yearly Report for the Saudi Council of Engineers (SCE 2019) because it is hard to find the total of civil engineers and architects who work in Saudi Arabia. Moreover, the total of civil engineers and architects registered with the Saudi Council of Engineers SCE is 67,081: 50,060 civil engineers and 17,021 architects. To ensure high accuracy for the sample size, this study used more than one method: Cochran (1963), Yamane (1967) and https://surveysystem.com/sscalc.html. The sample size of the three methods is relatively close, so the highest number will be used, which is 398.

a- The first method is Cochran (1963).

$$n_0 = \frac{z^2 \rho q}{e^2}$$

$$n_0 = \frac{(1.96)^2(0.5)(0.5)}{(0.05)^2}$$

$$n = \frac{n_0}{1 + \frac{(n_{0-1})}{N}}$$

$$n = \frac{384.2}{1+\frac{(384.2_{-1})}{67081}}$$ 382.02= 282

b- The second method is Yamane (1967).

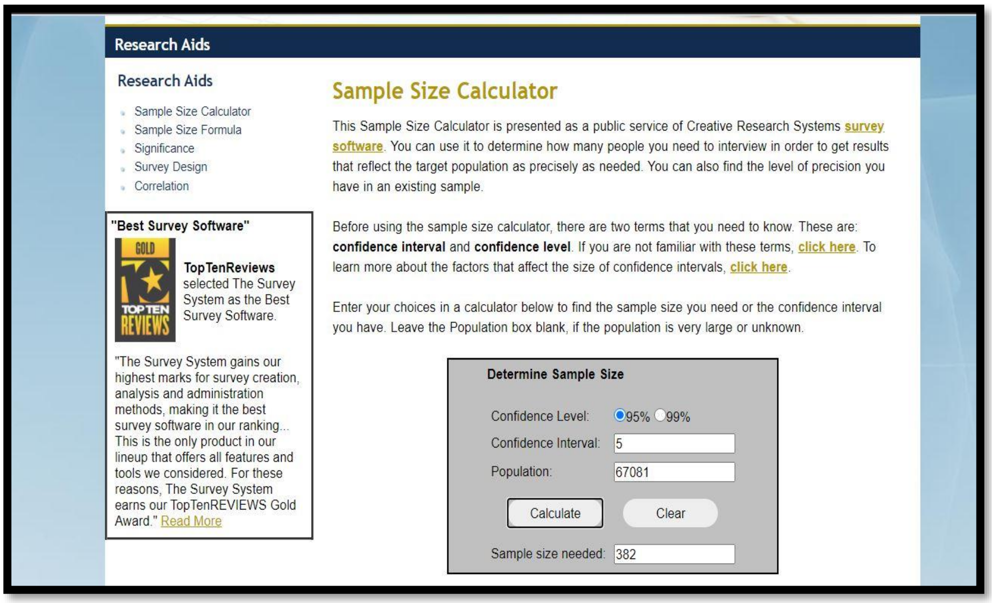
$$n = \frac{N}{1 + N(e)^2}$$

$$n = \frac{67081}{1 + 67081(0.05)^2} \quad 397.63 = 398$$

- n_0 is the sample size.
- Z^2 is the abscissa of the normal curve that cuts off an area at the tails.
- p is the margin of error.
- q is 1-p.
- e is the recommended level of precision.

N, meanwhile, is the population size of $\mathbf{67,081}$ according to the Saudi Council of Engineers (SCE).

c- The third method (https://surveysystem.com/sscalc.htm).



- Ethics.

In the field of research, "research ethics" refers to the norms of activities that control behaviour about the rights of individuals who are impacted by the study or become its subject. According to Saunders et al. (2012), the broader social norm of behaviour impacts the acceptability or appropriateness of a researcher’s conduct. For this study, the researcher applied the ethical approval to the School Ethics Office and Research Integrity at the Welsh School of Architecture in Cardiff University before the pilot testing and distribution of the questionnaire to the targeted sample. The questionnaire was sent to the participants after the approval from the committee. The ethics approval is provided in Appendix B.

- Data collection technique.

After the research ethics approval was received, the data collection was conducted from April 2021 to Jun 2021. The online questionnaire was hosted by Bristol Online Survey, https://www.onlinesurveys.ac.uk/. The survey link was sent through email and several social media applications (WhatsApp, Twitter, Instagram, Facebook, and Telegram) to reach sufficient participants. Specifically, this questionnaire was structured, piloted and then, distributed to architects and civil engineers online since it costs less and is quicker than manual printed surveys (Huang 2006; Weible and

Wallace 1998). The questionnaire went to 1129 participants, 491 of whom (43.49%) answered the questionnaire, and 638 of whom (56.51%) did not complete the questionnaire. Furthermore, only 398 responses were analysed because the study's sample size was calculated from the architects and civil engineers registered with the Saudi Council of Engineers SCE.

This study used the snowball sampling techniques presented by Coleman (1959) and Goodman (1961). The snowball sampling technique is believed to be an appropriate academic method for sampling (Frank and Snijders 1994). This method encourages the units that were sampled to share their information with other units (Frank and Snijders 1994). Additionally, Meyer and Booker (2001) stated that the snowball technique is a common method often employed in academic studies that engage individual experts. The snowball sampling technique has been thought to be effective, economical, and efficient (Singh et al. 2007). It makes it possible for the authors to identify a large number of members who want to remain anonymous, while at the same time allowing them to interact with and recognise informants who possessed specific expertise (Bird 2009).

- Data analysis

According to Bryman (2012), The use of statistical methods to data that has been collected, which may be primary or secondary data, is what is meant by the term "data analysis." The numerical data, sometimes known as "raw data," are converted into variables, which may then be analysed, using these methods (Sapsford and Jupp 1996). Furthermore, the primary objective of data processing is to transform the data that has been gathered into information in order to draw attention to the relevant and significant growing patterns and correlations within the data (Alreck et al. 1995). Statistical analysis is classified into two types: descriptive statistical analysis and inferential statistical analysis (Babbie 2020); this study used both types. The descriptive statistical analysis is used to provide characteristic descriptions of the participants such as age, gender, and academic qualifications. Also, it is used to describe the mean, median, standard deviation etc. Inferential statistical analysis is used to test the hypothesis of each attribute (Babbie 2020).

- Processes of Analysis

Following the online questionnaire, the collected data from the questionnaire were arranged as following:

1. **Grouping:** The questionnaire was sent to the participants in two different copies, Arabic and English. After receiving all the responses, the researcher combined the two copies into one copy in excel.
2. **Coding:** When preparing the raw data to analyse a questionnaire, coding is an essential part (Sapsford and Jupp 1996). The coding for the questionnaire was done for easy identification and to prepare the data to be entered into the statistical software. An example of the coding for each question is the question that has a Likert scale (1 - strongly disagree, 2 - disagree, 3 - neutral, 4 - agree, 5 - strongly agree).
3. **Data Entry:** After coding, the data were exported to Statistical Package for the Social Sciences (SPSS) version 27, which will be utilized to the questionnaire analysis.

- Descriptive statistical test

a- Percentage distributions

To investigate the patterns of responses in this study, number and percentage distribution were constructed. Argyrous (1997) states that the percentage distribution shows how the different variables in the category are distributed among each observation. Furthermore, the percentage distribution was used towards the investigation of the socio-demographic characteristics of participants. Gender, age, profession, academic qualification, work experience and awareness of 3D printing technology in the construction industry have been considered before participating in the survey.

b- Testing each attribute independently

Each attribute (Relative Advantage, Complexity (Ease to use), Compatibility, Observability and Trialability) will be analysed using mean ranking (Bakir 2021). From the participants' view, this ranking scale indicated the most important item in each attribute. This will be done by ranking the mean value from the highest to the lowest in each attribute.

- **Inferential statistical analysis**

a- Hypotheses testing

For the hypothesis testing, originally the researcher planned to use a parametric test (one-sample t-test) to compare the sample's mean to a given value (Gerald 2018). t-test requires that the data are normally distributed (Gerald 2018). However, after the researcher tested the normality of the data distribution, it was found that the data were not distributed normally. The researcher attempted to normalise the data by using log transformation (Wang et al. 2014). However, the attempt to normalise the data failed, so the researcher decided to choose a non-parametric test. Non-parametric tests are tests that do not presume a specific data distribution (Gerald 2018). For the hypothesis testing in this study, the Sign Test is used. The Sign Test was designed toward the investigation of the median difference between the paired samples (Fong et al. 2003). It is a reasonable test since it does not rely on any population distributional assumptions (Fong et al. 2003). The interpretation of the sign test is, If the P-value < 0.05, the results are significant (Ho 2006). Furthermore, given the previous definition for the Sign Test assumptions and interpretation, it was found that the Sign Test is the most appropriate test to be done for testing the hypothesis for this study.

3.4. Methodology Framework.

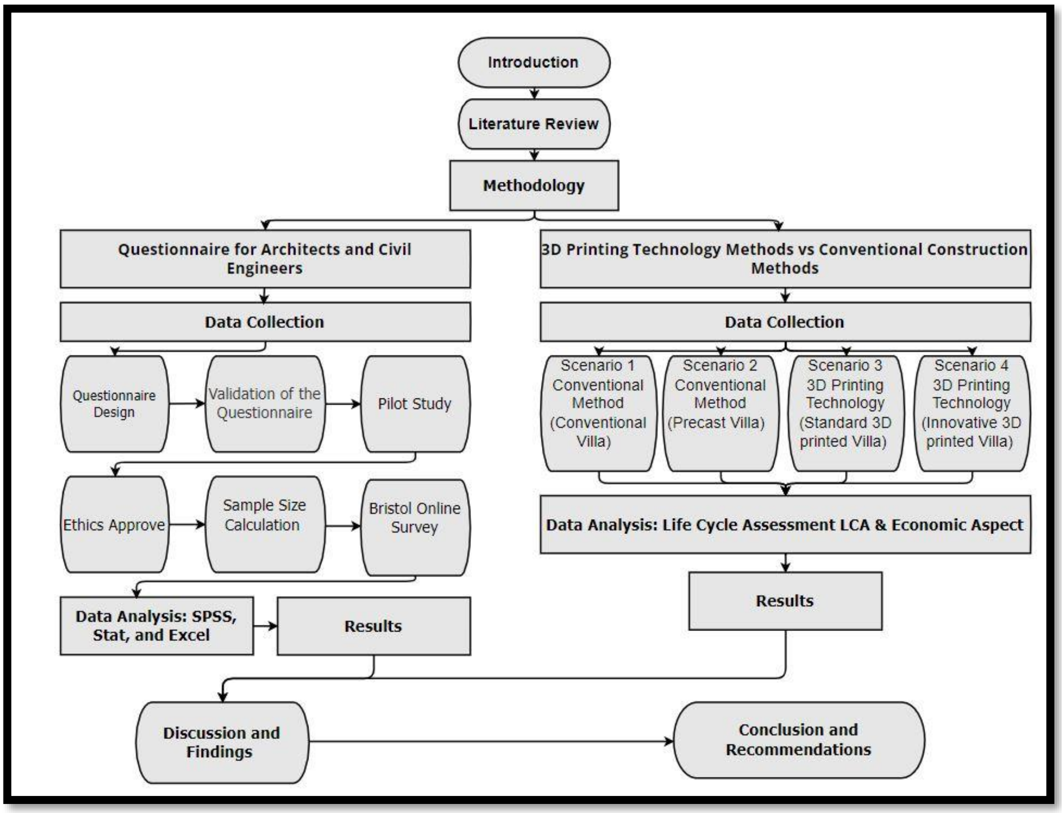


Figure 3-16 Thesis Framework.

3.5. Chapter Summary.

The chapter described a comprehensive examination of the methodology and methods implemented within the study. It has been confirmed after consideration of several alternatives that a quantitative approach is the chosen method based on the nature of the research aim and objectives. A positivist paradigm was the highly suitable philosophical paradigm for this study, allowing quantitative data to be collected using the experimental method (LCA) and questionnaires method (DIT). All the chosen tools in the methodology have been fully justified. The next chapter presents the results of the Life Cycle Assessment (LCA) and economic analysis for 3D printing technology vs conventional construction methods.

Chapter 4: The Environmental and Economic Results and Analysis of 3D Printing Technology vs Conventional Construction Methods.

4.1. Introduction.

This section demonstrates the outcomes for the environmental aspect LCA and the economic aspect of comparing 3D printing technology and conventional construction methods. The assessment will be done on a one-storey villa in Al Khobar, Saudi Arabia with four different construction scenarios as presented in Sections 3.3.1. in Chapter 3. This chapter is divided into two major sections: Sections 4.2. and 4.3. present the environmental aspect LCA and economic analysis of both 3D printing technology and conventional construction methods. The LCA section includes three parts: a primary comparison of the four scenarios, the breakdown of materials for each scenario and a sensitivity analysis performed for each scenario. Furthermore, the economic analysis section consists of two parts: a primary comparison for the economic analysis between the four scenarios and a detailed breakdown of the material and construction cost for each scenario. The last Section 4.4. shows a brief review of the results.

4.2. Environmental Aspect (Life Cycle Assessment LCA) Analysis.

This part demonstrates the outcomes of the LCA in three steps. The initial step will compare the four houses' scenarios that were presented in chapter 3 in terms of their environmental impacts. After that, the impact of each house type will be broken down in the second step. The purpose of this analysis is to establish which process and/or material has the highest impact on the environment among all scenarios. After determining the factors that contribute the most, the third phase involves doing a sensitivity analysis for each scenario and to determine the environmental impact changes. The results of the assessments carried out in SimaPro were first presented in the form of characterised values, which illustrated the degree to which each of the scenarios varied in terms of their impact on the environment (Figure 4-1).

The characterised findings need to be normalised and weighted according to the PEFCR guidance in order to provide a holistic overview assessment of the overall influence of the products. This may be done by applying certain factors to the results (European-Commission 2019). After that, the findings that have been normalised and weighted may be utilised as an accurate description of the performance across all of the impact categories combined. For instance, the described values in (Table4-1), have been normalised with the guidance of the normalisation (NF/person) and weighting factors. This led to an improvement in the overall performance of each scenario when compared to the first scenario (conventional villa). As explained in Chapter 2, seven out of 18 impact factors in the ReCiPe impact method will be analysed. However, the characteristics for all the 18 factors are presented in Appendix C. Also, the results in this chapter are presented by percentage. To obtain the detailed results of each method see Appendix C.

4.2.1. Primary Comparison.

The findings of all the scenarios show that the conventional villa scenario had the highest overall impact on the environmental. The Precast Villa scenario accomplished a collective 0.3%, which is almost the same as the conventional villa scenario. Furthermore, the Standard 3DP Villa scenario demonstrated better environmental performance than the Conventional villa scenario with 44%. The Innovative 3DP Villa scenario achieved the highest environmental performance of all villas, especially the conventional villa, where it recorded 47% (Figure 4-1) and (Table 4-1).

When focusing on each construction method separately, the results revealed no big difference between each technique. When comparing the two techniques within the conventional construction method, the precast villa was better in six categories, except in Marine eutrophication (Figure 4-1) and (Table 4-1). On the other hand, in the 3DP construction method, the 3DP Innovative villa has a better environmental performance in all categories except Land use, where the 3DP standard villa has an improvement of 0.8%.

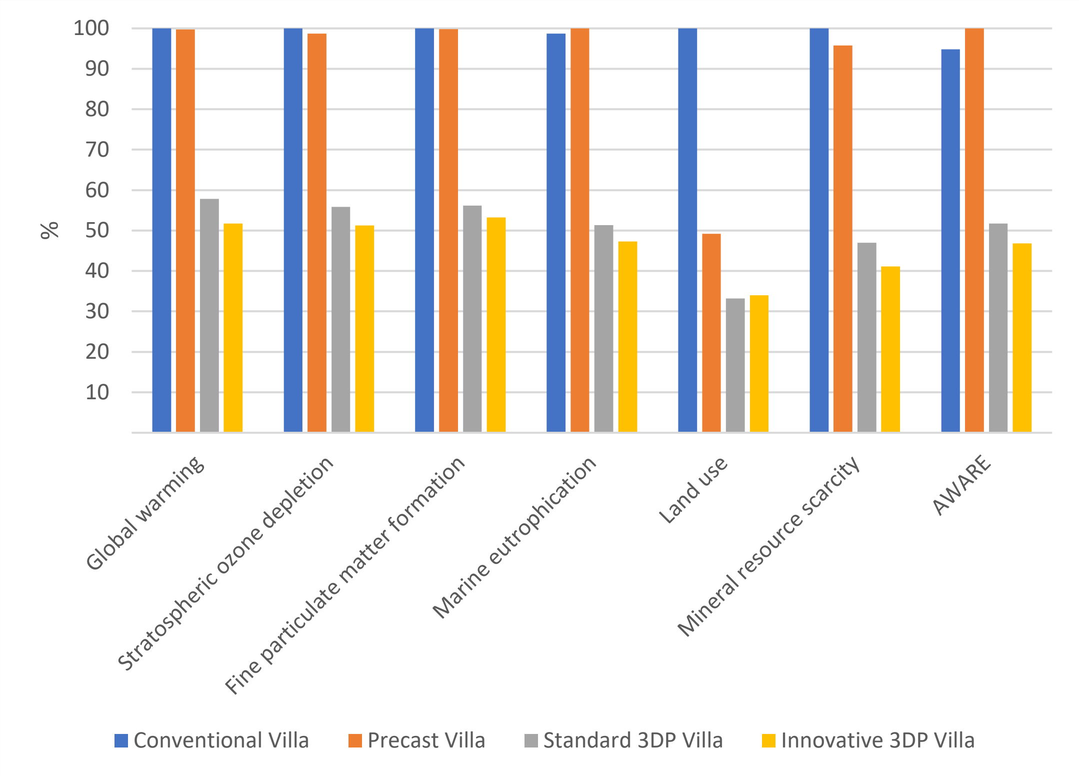


Figure 4-1 Overall Outcome of Comparing the Four House Scenarios.

Table 4-1 Percentage of Improvement in the Environmental Performance of the House Scenarios as Compared to the Conventional Villa Scenario. (NF: Normalisation factor; WF: Weighting Factor).

Impact categories	**NF/person**	**WF/person**	**Precast Villa**	**Standard 3DP Villa**	**Innovative 3DP Villa**
Global warming	8095.53	22.19	0.30%	42.20%	48.20%
Stratospheric ozone depletion	5.37E-02	6.75	1.30%	44.20%	48.70%
Fine particulate matter formation	5.95E-04	9.54	0.20%	43.80%	46.70%
Marine eutrophication	19.545	3.12	-1.30%	48%	52.10%
Land use	8.19E+05	8.42	50.80%	66.80%	66%
Mineral resource scarcity	6.36E-02	8.08	4.40%	53%	58.80%
AWARE (water depletion)	11468.7	9.03	-5.40%	45.40%	50.70%
Overall improvement	--	--	0.30%	44%	47%

4.2.2. The Breakdown of Materials for Each Construction Method.

In order to gain a more in-depth understanding of the findings, each scenario was analysed separately by breaking down the materials in order to determine the influence of each sub-material. In addition, the total contribution of each category was evaluated, with a particular emphasis placed on global warming as being the most important category in terms of its influence. The results were normalised and weighted for each impact category. First, the findings for the standard villa scenario indicated that the reinforcing steel contributed the most to the environmental impact, at 52% in all categories, except for Mineral resource scarcity, in which plywood recorded the highest. The second-highest environmental impact contributor in all categories was the concrete mix with an overall of 23%, except for plywood in land use. Ceramic tiles came up as the third-highest contributor with a total of 11% in all categories, except cement mortar, transportation, and Polystyrene in global warming. Moreover, the window frame (aluminium) and cement mortar had a higher impact on Marine eutrophication (Figure 4-2). Additionally, in the 3D printing technology, using the gantry system such as COBOD 2 will make a difference in the printing time more than a robot arm such as the KUKA robot. The gantry system could cover more area 300 m^2 up to than the robot arm, which is limited to 3 to 4 m^2 (Delgado Camacho et al. 2018; COBOD 2019).

The impact breakdown of the Precast villa shows that 45% of the contribution came from reinforcing steel in all categories, except for concrete mix and gypsum fibreboard in Global warming. Similarly, paint, Bitumen adhesive compound, Steel sheets, Bitumen seal, ceramic tiles, Gypsum fibreboard and Double-glazing windows recorded a higher contribution to Land use. In AWARE (water depletion), Polyethylene had a higher impact than reinforcing steel.

The concrete mix was the second-highest environmental impact contributor with 25% overall in all categories, except for gypsum fibreboard in Global warming and reinforcing steel in Fine particulate matter formation, Marine eutrophication, and Mineral resource scarcity. In Land use, steel sheets had a higher contribution than concrete mix.

Ceramic tiles came third with a 12% impact in all categories, except for steel sheet, reinforcing steel, concrete mix, transportation, and gypsum fibreboard in Global-

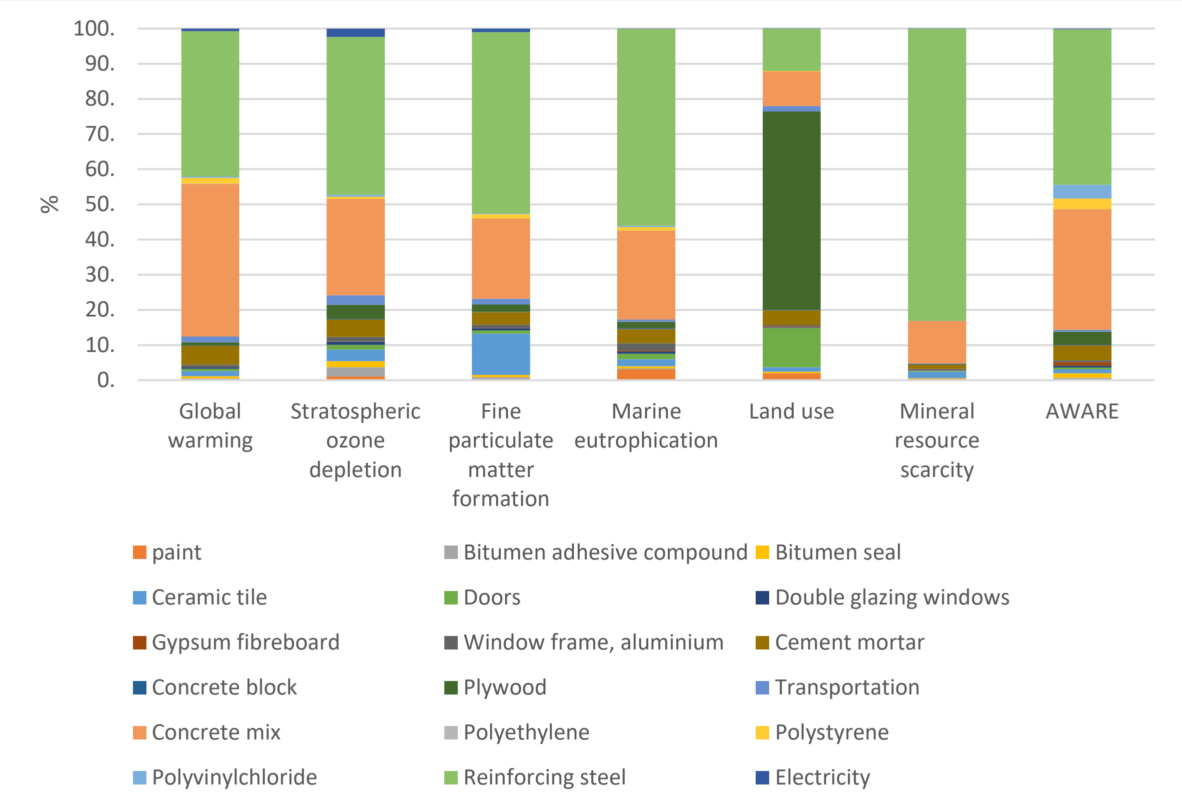


Figure 4-2 Chart Shows the Breakdown of Impacts in a Conventional Villa Scenario .

warming. Bitumen adhesive compound, Bitumen seal, transportation, concrete mix, reinforcing steel, Electricity and Steel sheets also scored higher than ceramic tiles in the Stratospheric ozone depletion. Concrete mix and reinforcing steel recorded a higher impact score on Fine particulate matter formation, while Steel sheet, reinforcing steel, concrete mix and paint contributed more to Marine eutrophication. In Land use, Steel sheets, Electricity, Polystyrene, Polyethylene, transportation, Gypsum fibreboard, Double glazing windows, Bitumen seal and paint recorded higher contributions than ceramic tiles. Reinforcing steel, concrete mix and Steel sheets contributed more to Mineral resource scarcity. Polyvinylchloride, reinforcing steel, Steel sheets, Polystyrene, Concrete mix, Polyethylene and Bitumen seal had a higher contribution than ceramic tiles in AWARE (water depletion) (Figure 4-3).

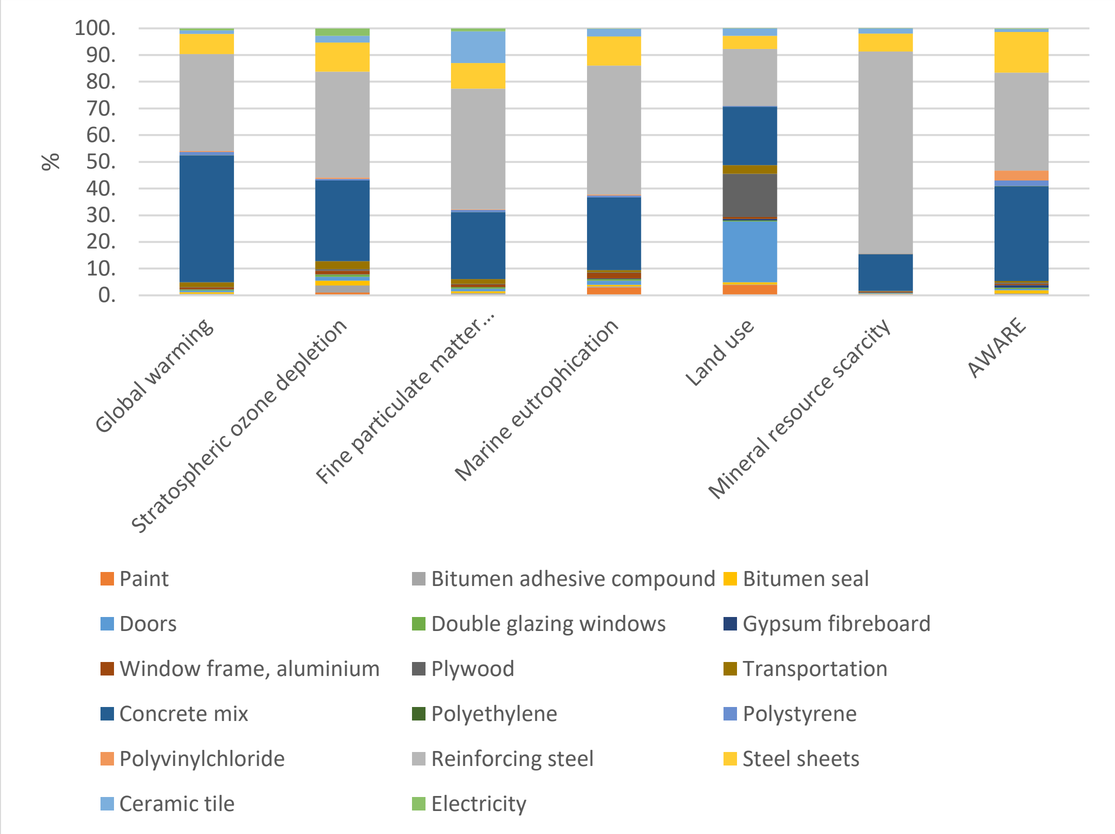


Figure 4-3 Chart Shows the Breakdown of Impacts in a Precast Villa Scenario.

The impact breakdown for the third scenario, which is a 3DP standard villa, showed that reinforcing steel had the highest contribution in all categories with 32% environmental impact, except for fibre, concrete mix, and robot transportation in Global Warming. Bitumen adhesive compound, robot transportation and fibre also had a higher contribution to AWARE (water depletion). The concrete mix came second with 18% environmental impact in all categories, other than fibre in Global Warming, reinforcing steel in Stratospheric ozone depletion and reinforcing steel in Fine particulate matter formation and Marine eutrophication. In Land use, Cement and fly ash, polycarboxylates, fibre, sand gravel and quarry, robot transportation, reinforcing steel, window frame (aluminium), double glazing windows, windows, ceramic tile, polystyrene, polyethylene, bitumen seal, bitumen adhesive compound, paint, material, electricity, and transportation had a higher contribution. Reinforcing steel had a higher contribution to Mineral resource scarcity than concrete mix, while bitumen adhesive compound, robot transportation and fibre were higher contributors in AWARE (water depletion). Finally, ceramic tiles and gypsum fibreboard came third with an overall contribution of 16.3% from each of them (Figure 4-4).

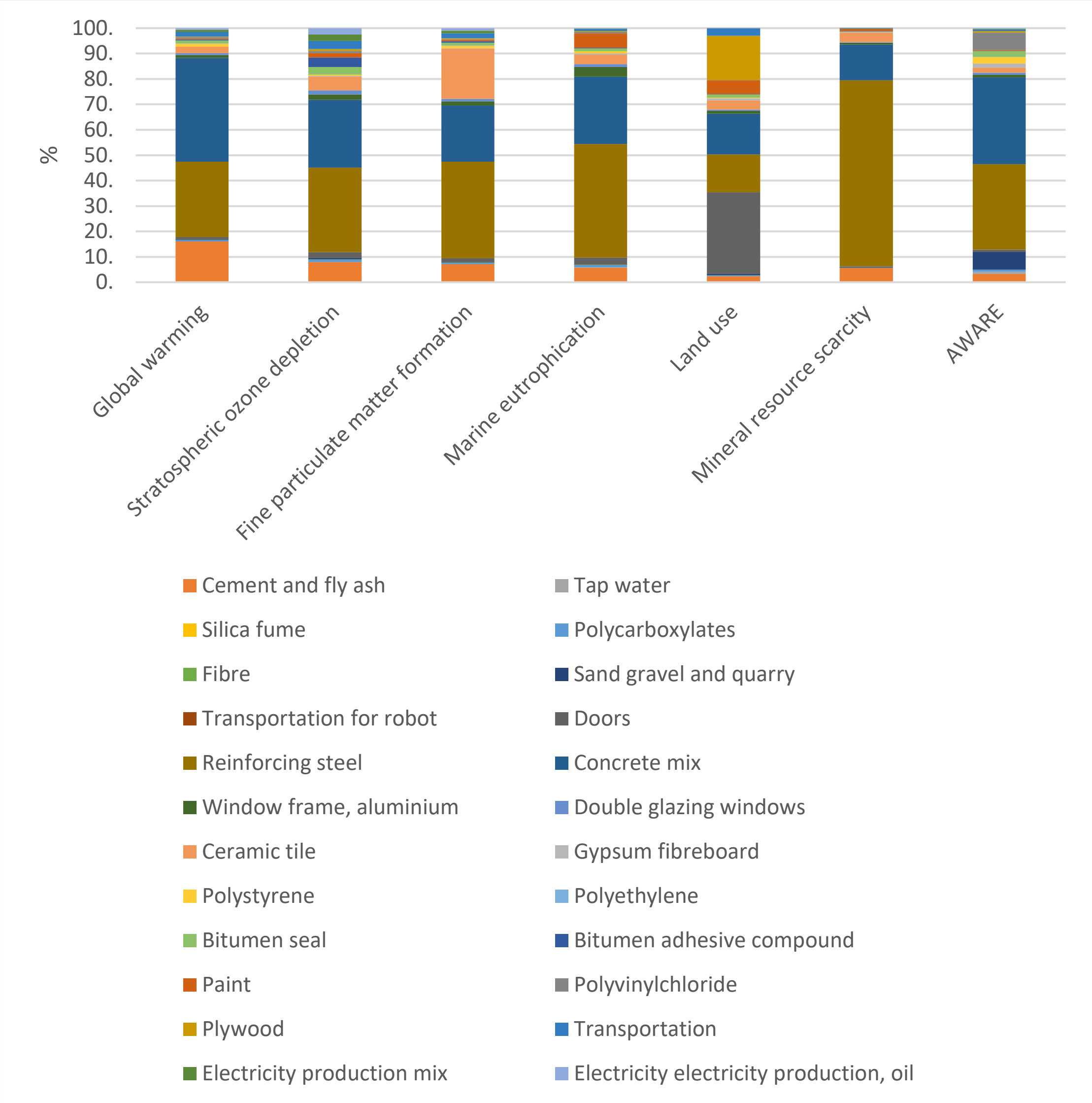


Figure 4-4 Chart Shows the Breakdown of Impacts in a 3DP Standard Villa Scenario.

The impact breakdown for the last scenario, a 3DP innovative villa, shows that the highest environmental impact came from reinforcing steel with 34% in all categories, except for fibre, concrete mix, and gantry transportation in Global Warming. In Land use, concrete mix, Bitumen adhesive compound and plywood had a higher impact than reinforcing steel. Furthermore, in AWARE (water depletion), fibre, gantry transportation and Bitumen adhesive compound had a higher impact than reinforcing steel.

Ceramic tiles came second for the highest environmental impact with 23.8% in all categories, except for reinforcing steel, concrete mix, gantry transportation, fibre and Cement and fly ash in Global Warming. In the Stratospheric ozone depletion too, concrete mix and reinforcing steel had a higher impact than Ceramic tile, whereas only reinforcing steel had a higher impact on Fine particulate matter formation. Paint, Cement and fly ash, Window frame (aluminium), concrete mix and reinforcing steel also had a higher impact than Ceramic tiles on Marine eutrophication. In Land use, fibre, reinforcing steel, concrete mix, Window frame (aluminium), Double glazing windows, Polyethylene, Bitumen seal, Bitumen adhesive compound, paint and plywood had a higher impact than ceramic tile. Reinforcing steel and concrete mix had a higher impact than Ceramic tiles on Mineral resource scarcity. Finally, in AWARE (water depletion), Polyvinylchloride, Bitumen adhesive compound, Polystyrene, concrete mix, reinforcing steel, gantry transportation, Sand gravel and quarry, fibre and Cement and fly ash had a higher impact than ceramic tile.

The material with the third-highest environmental impact on the 3DP innovative villa was concrete mix with 21.6% in all categories, except for gantry transportation and fibre in Global Warming. In Stratospheric ozone depletion, reinforcing steel had a higher impact than concrete mix, while Ceramic tiles and reinforcing steel had a higher impact on Fine particulate matter formation. Similarly, reinforcing steel had a higher impact on Marine eutrophication and Mineral resource scarcity. Bitumen adhesive compound also had a higher impact on Land use. Lastly, in AWARE (water depletion), Ceramic tiles and reinforcing steel had a higher impact than a concrete mix (Figure 4-5).

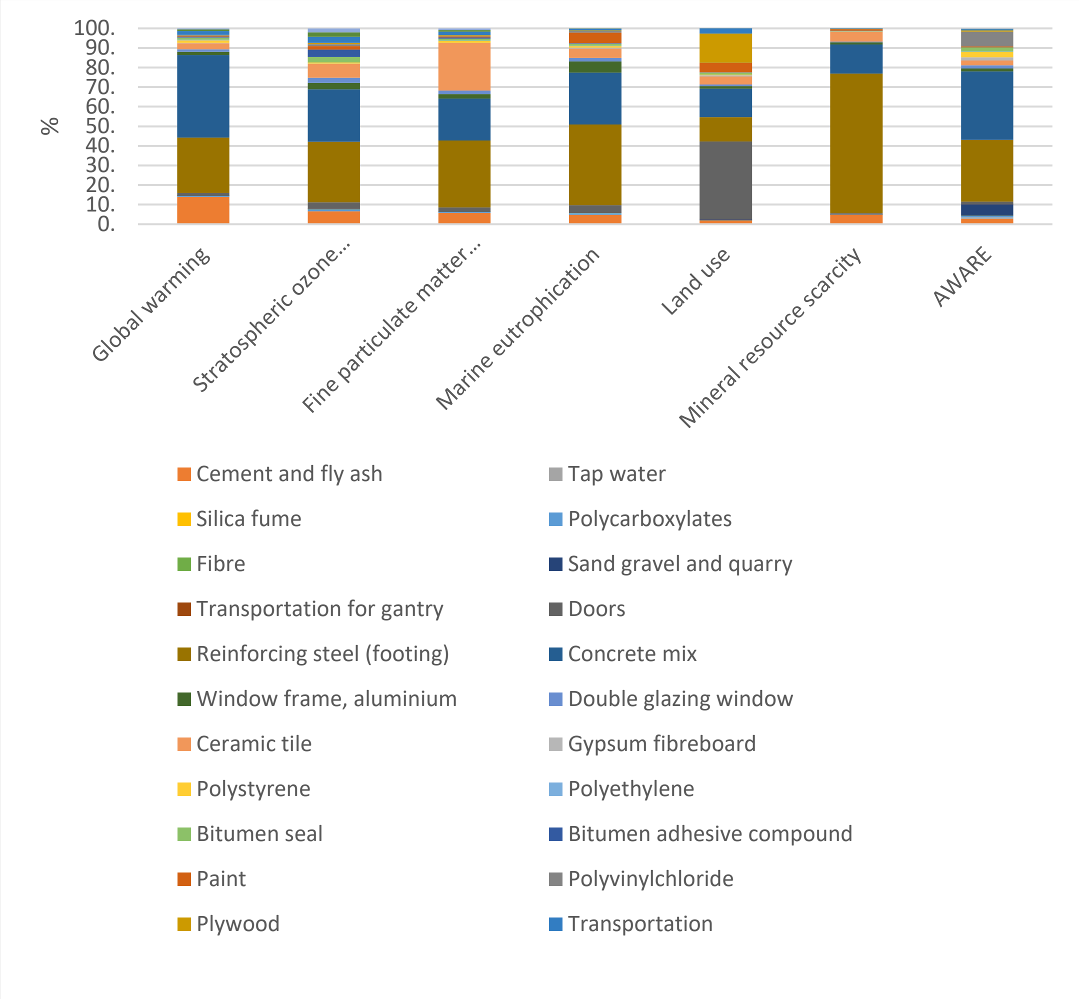


Figure 4-5 Chart Shows the Breakdown of Impacts in a 3DP Innovative Villa Scenario.

4.2.2.1. Sensitivity Analysis.

On the basis of the preceding findings, it is essential to investigate the sensitivity of some materials that have been found to having a substantial influence on the environment and to determine how this impact might be improved upon or reduced. For the purpose of this study, the sensitivity analysis was conducted based on the four different scenarios:

- Changing the type of foundation from raft foundation to isolated foundation in a conventional villa.
- Changing the ceramic tiles to epoxy floor paint in a precast villa.
- Changing the ceramic tiles to epoxy floor paint in a 3DP standard villa.
- Changing the ceramic tiles to epoxy floor paint in a 3DP innovative villa.

- Conventional Villa

As pointed out previously, reinforcing steel had the highest environmental impact contribution in conventional villa scenario. It was found that most of the reinforcing steel was in the foundation. So, to reduce the amount of reinforcing steel used, the foundation was changed from a raft foundation to an isolated foundation. The calculation for the new foundation system was done by a civil engineer who has experience in the housing sector in Saudi Arabia (Figure 4-6) and (Table 4-2).

Due to the change in the footing system, the amount of concrete, bitumen paint, plywood and steel in the isolated footing was also changed. The amount of concrete was reduced from 238.38 m^3 to 133 m^3, while the reinforcing steel amount was reduced from 37.32 tons to 31.29 tons. On the other hand, plywood quantity was increased from 0.49 m^3 to 3.13 $m^{3,}$ and bitumen paint from 377 m^2 to 420.19 m^2. The change of the foundation enhanced the overall performance by 25% and 29% in the global warming category when compared to the raft foundation. However, in Land use, the raft foundation had a better performance of 13% (Figure 4-7) and (Table 4-3).

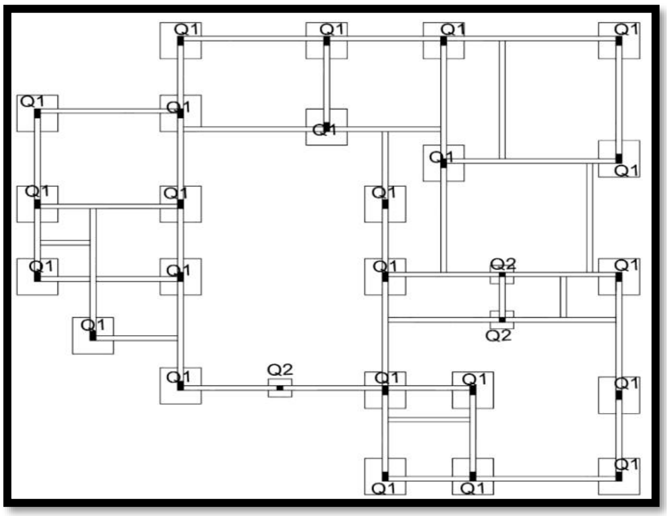


Figure 4-6 Conventional Villa With Isolated Footing.

Table 4-2 Specifications of Isolated Footing.

Footing type	Dimensions of reinforced concrete			Lower reinforcement		Upper reinforcement	
	Length	Width	Height	Length	Width	Length	Width
Q1	1.6	1.4	0.5	7Ø16	7Ø16	2Ø16	3Ø16
Q2	0.8	0.8	0.5	6Ø14	6Ø14	--	--

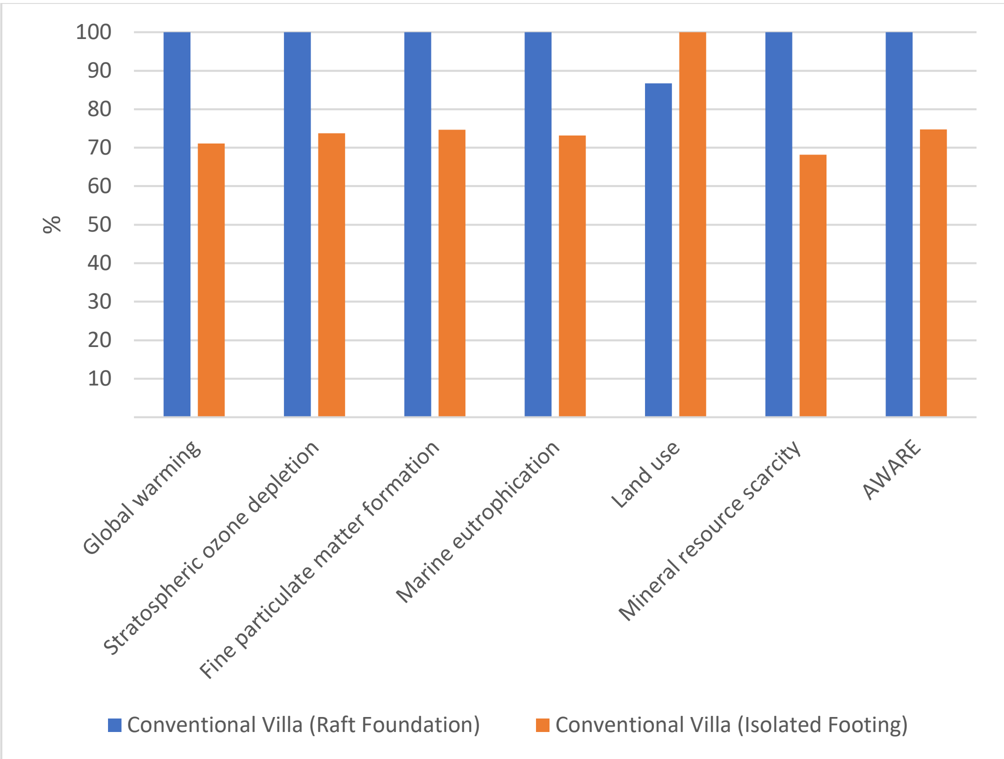


Figure 4-7 Comparing Raft Foundation to the Isolated Footing in a Conventional Villa Scenario.

Table 4-3 Percentage of Improvement Between Conventional Villa Scenario (Raft Foundation).

Impact categories	Raft Foundation	Isolated footing
Global Warming	--	29%
Stratospheric Ozone Depletion	--	26%
Fine Particulate Matter	--	25%
Marine Eutrophication	--	27%
Land Use	13%	--
Mineral Resource Scarcity	--	32%
AWARE	--	25%
Overall Improvement	--	25%

- Precast Villa

As mentioned earlier, reinforcing steel and concrete mix achieved the highest environmental impact in a precast villa scenario. In this case, the foundation system cannot be altered due to the Saudi Building Code regulations; therefore, the change will be applied to the material with the third-highest impact—ceramic tiles. More than one material is used in flooring in Saudi Arabia, such as Laminate flooring, marble flooring, epoxy, and carpet. For this study, epoxy floor paint was chosen to replace ceramic tiles due to its low manufacturing cost, excellent chemical corrosion resistance, high stiffness, and good mechanical properties (S.Z. et al. 2014). Another reason for choosing epoxy floor paint is because of an environmental comparison made between epoxy floor paint and Laminate flooring, which found that epoxy floor paint had a better environmental performance comparatively. The results of the study indicated that changing ceramic tiles to epoxy floor paint improved the performance of a precast villa by an overall of 12% and 1% in the global warming category in comparison to ceramic tiles (Figure 4-8) and (Table 4-4).

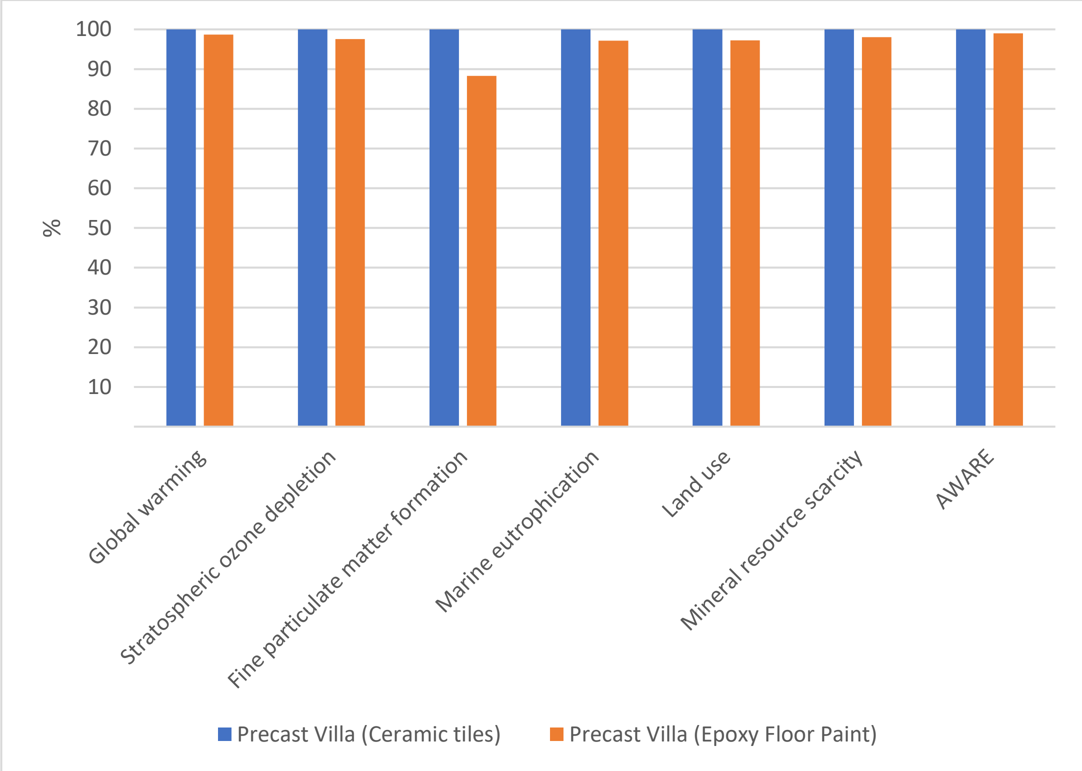


Figure 4-8 Comparing Ceramic Tiles to Epoxy Floor Paint in a Precast Villa Scenario.

Table 4-4 Percentage of Improvement Between Precast Villa Scenario (Ceramic tiles) and Precast Villa Scenario (Epoxy Floor Paint).

Impact categories	**Precast Villa (Ceramic tiles)**	**Precast Villa (Epoxy Floor Paint)**
Global Warming	--	1%
Stratospheric Ozone Depletion	--	2%
Fine Particulate Matter	--	12%
Marine Eutrophication	--	3%
Land Use	--	3%
Mineral Resource Scarcity	--	2%
AWARE	--	1%
Overall Improvement	--	12%

- 3DP Standard Villa

In a 3DP standard villa scenario, the results indicated that reinforcing steel and concrete mix achieved the highest environmental impacts in all categories. Since reinforcing steel and concrete mix are in the raft and cannot be changed, the ceramic tiles were compared with epoxy floor paint. The results show that changing ceramic tiles to epoxy floor paint improved the performance of the precast villa by 20% overall and 2% in the global warming category when compared to ceramic tiles (Figure 4-9) and (Table 4-5).

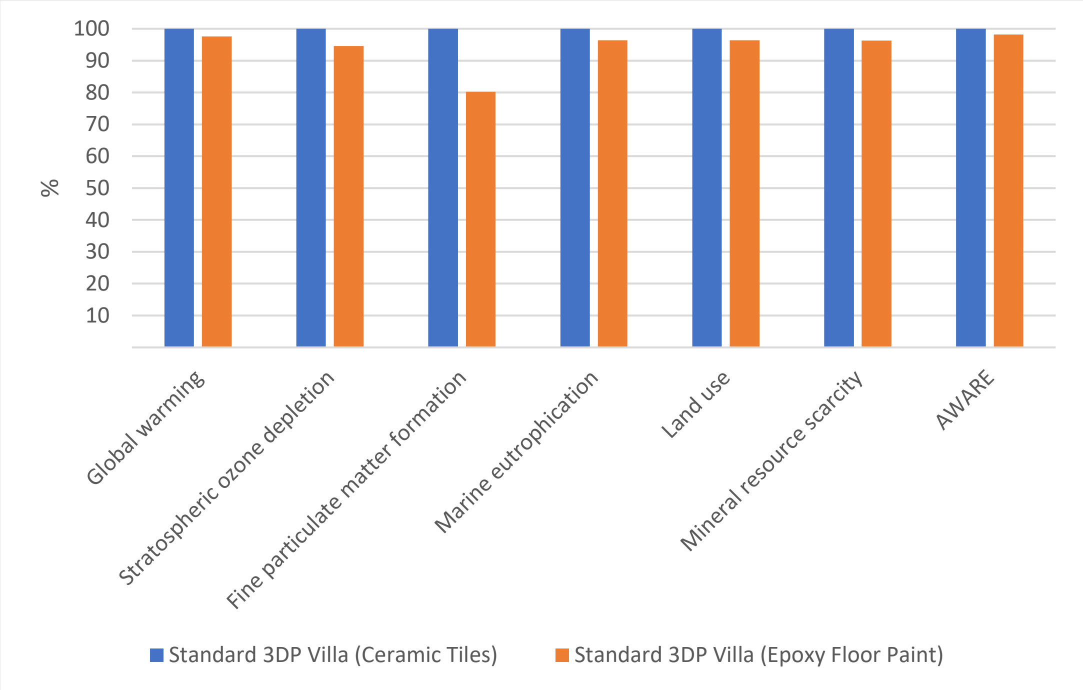


Figure 4-9 Comparing Ceramic Tiles to Epoxy Floor Paint in a 3DP Standard Villa Scenario.

Table 4-5 Percentage of Improvement Between a 3DP Standard Villa Scenario (Ceramic tiles) and a 3DP Standard Villa Scenario (Epoxy Floor Paint).

Impact categories	**3DP standard Villa (Ceramic tiles)**	**3DP standard Villa (Epoxy Floor Paint)**
Global Warming	--	2%
Stratospheric Ozone Depletion	--	5%
Fine Particulate Matter	--	20%
Marine Eutrophication	--	4%
Land Use	--	4%
Mineral Resource Scarcity	--	4%
AWARE	--	2%
Overall Improvement	--	20%

- 3DP Innovative Villa

The same change was applied to a 3DP Innovative villa scenario, where a comparison was made between ceramic tiles and epoxy floor paint. The results suggested that changing ceramic tiles to epoxy floor paint improved the performance of a precast villa by 24% overall and 3% in the global warming category when compared to ceramic tiles (Figure 4-10) and (Table 4-6).

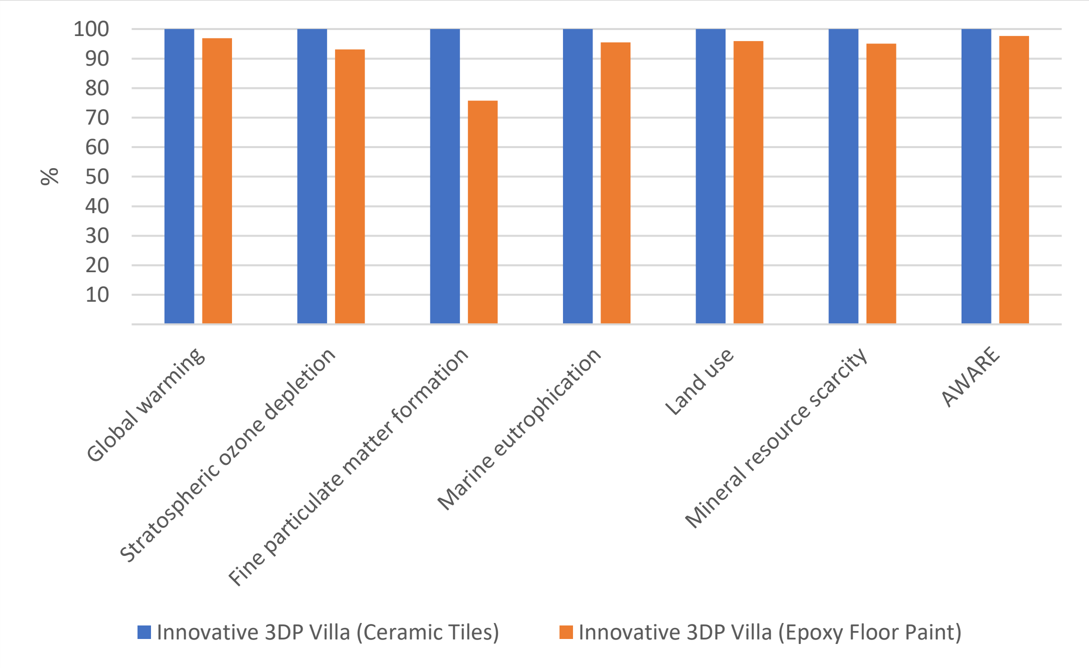


Figure 4-10 Comparing Ceramic Tiles to Epoxy Floor Paint in a 3DP Innovative Villa Scenario.

Table 4-6 Percentage of Improvement Between a 3DP Innovative Villa Scenario (Ceramic tiles) and a 3DP Innovative Villa Scenario (Epoxy Floor Paint).

Impact categories	**3DP Innovative Villa (Ceramic tiles)**	**3DP Innovative Villa (Epoxy Floor Paint)**
Global Warming	--	3%
Stratospheric Ozone Depletion	--	7%
Fine Particulate Matter	--	24%
Marine Eutrophication	--	5%
Land Use	--	4%
Mineral Resource Scarcity	--	5%
AWARE	--	2%
Overall Improvement	--	24%

4.3. Economic Analysis.

As motioned earlier in Chapter 3, Section 3.3.2., the assessment of the economic aspect (cost analysis) of comparing conventional and 3D printing technology construction methods will be done on the internal and external walls for the four scenarios without the finishing phase. This section represents a primary comparison for the four scenarios, the calculation of the materials cost and the construction cost for each. For more details regarding the calculation see Appendix D.

4.3.1. Primary Comparison.

The results indicate that by comparing the total cost for the four scenarios of the chosen villas, the precast villa comes out at the top at 118,324 SAR. The conventional villa has the second-highest cost with a total amount of 66,902 SAR. The standard 3D printed villa came third with a total of 33,144 SAR, and the Innovative 3D printed villa came last as the most inexpensive villa at 29,449 SAR. As for the construction time, an innovative 3D printed villa needs 6 days to be constructed. Meanwhile, 7 days are required for a standard 3D printed villa, 10 days for a precast villa and 16 days for a conventional villa (Table 4-7).

Table 4-7 Primary Comparison Between the Four Types of Walls.

Villa type	Cost of materials (SAR)	Cost of construction (SAR)	Total Amount (SAR)	Days for the project to be completed
Scenario 1 Conventional Villa	50,884	16,018	66,902	16
Scenario 2 Precast Villa	95,260	23,064	118,324	10
Scenario 3 Standard 3D printed Villa	23,454	9,690	33,144	7
Scenario 4 Innovative 3D printed Villa	21,154	8,296	29,449	6

4.3.2. Breakdown for Materials and Construction Cost.

- Scenario 1- Conventional Villa

The results for the material cost indicate that concrete masonry units (CMU) for outside and inside had the highest cost among other materials at 17,080 SAR. Sand, which was used for mortar for walls and CMU, came second with a total cost of 12,632 SAR. Additionally, steel bars used in columns came third with a total cost of 8,523 SAR, and cement bags came fourth at 7,220 SAR (Figure 4-11). Regarding the construction cost, the salary of labourers and engineers was the highest compared to the electricity production oil (Diesel) and formwork material (Plywood), at 15,957 SAR out of 16,018 SAR (Figure 4-12).

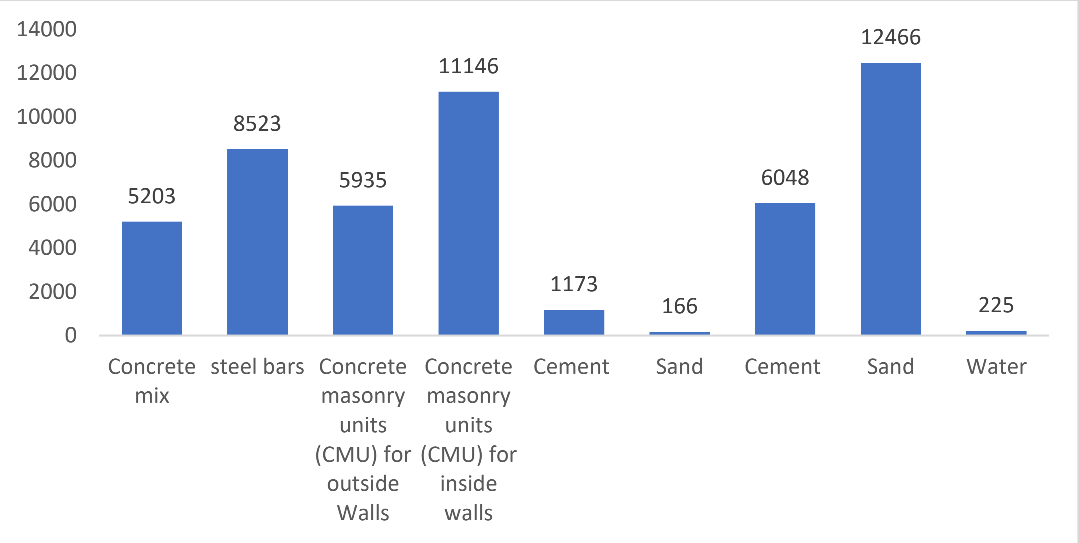


Figure 4-11 Material Cost for Scenario 1: Conventional Villa.

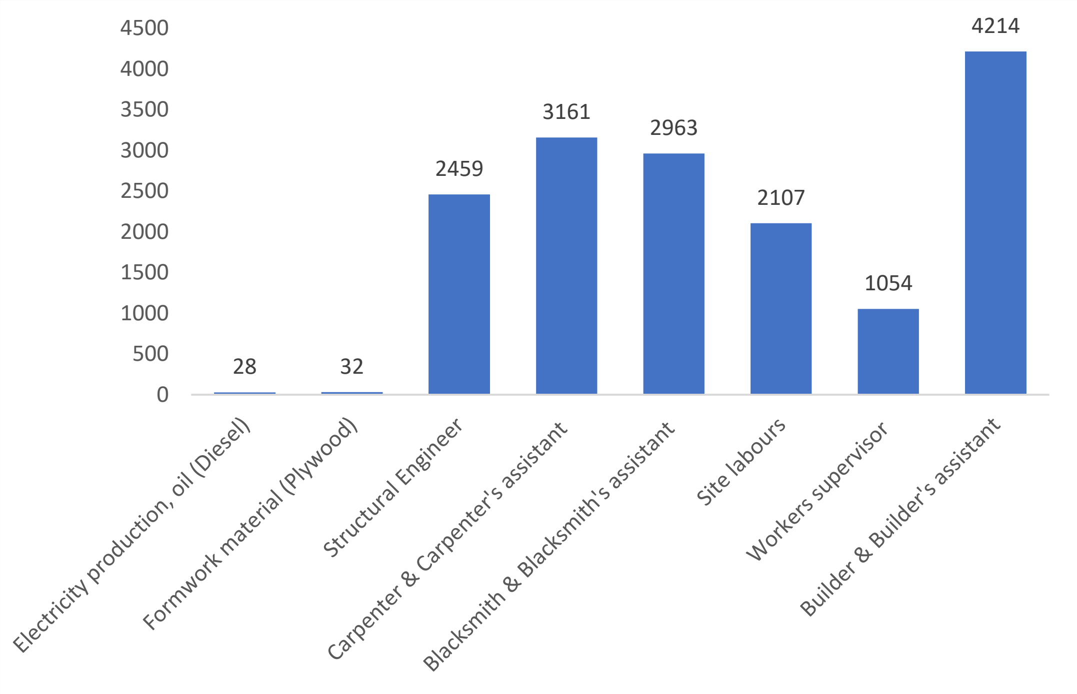


Figure 4-12 Construction Cost for Scenario 1: Conventional Villa.

- Scenario 2: Precast villa

In the precast villa, the concrete mix had the highest contribution to material cost at 64, 503 SAR. Steel bars came second with a total of 28,005 SAR (Figure 4-13). In the construction cost, like the conventional villa, the salary of labourers and engineers had the highest contribution compared to electricity production and formwork material (steel sheets) at, 14,997 SAR out of 23,064 SAR (Figure 4-14).

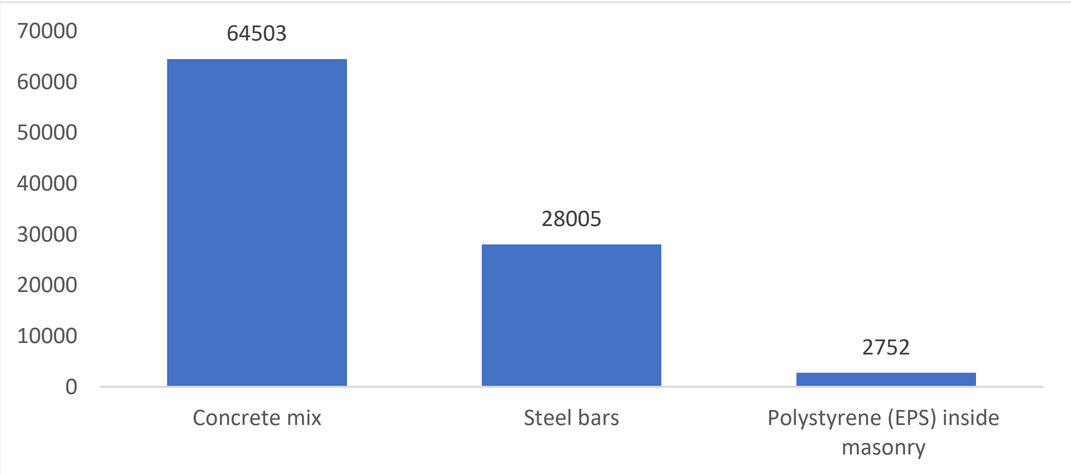


Figure 4-13 Material Cost for Scenario 2: Precast Villa.

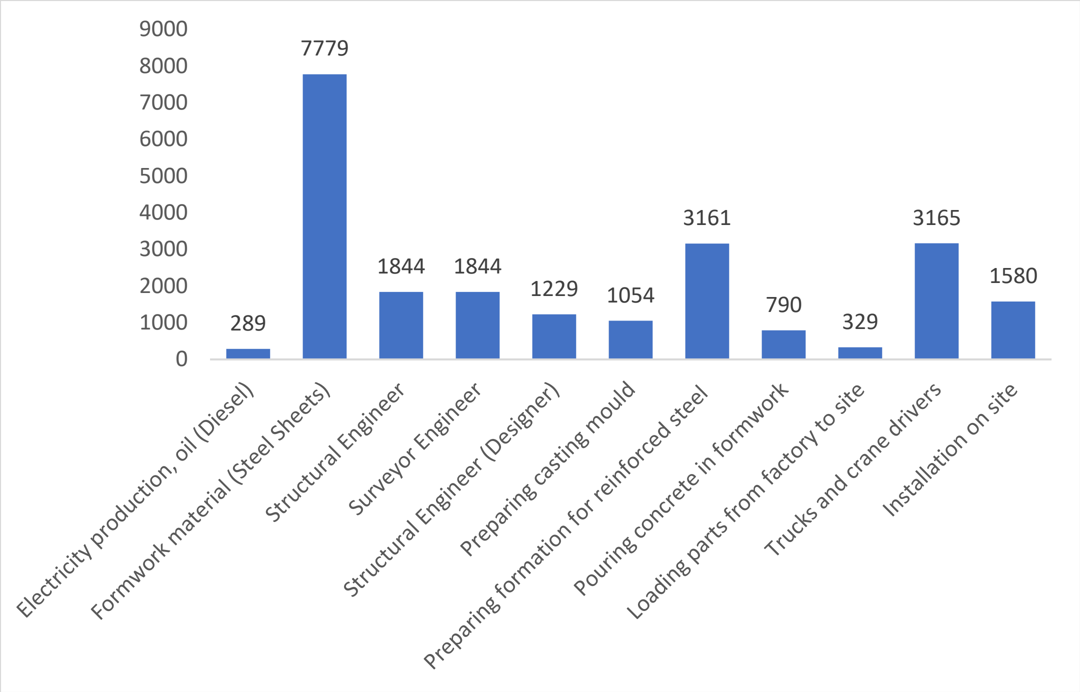


Figure 4-14 Construction Cost for Scenario 2: Precast Villa.

- Scenario 3: 3DP Standard Villa

The material cost for a standard 3D printed villa was unsurprisingly low since the 3D printing concrete mix is the only material used due to a lack of framework in the structure (Figure 4-15). In the construction cost analysis, the salary of labourers and engineers had the highest cost at 9,416 SAR out of 9,690 SAR (Figure 4-16).

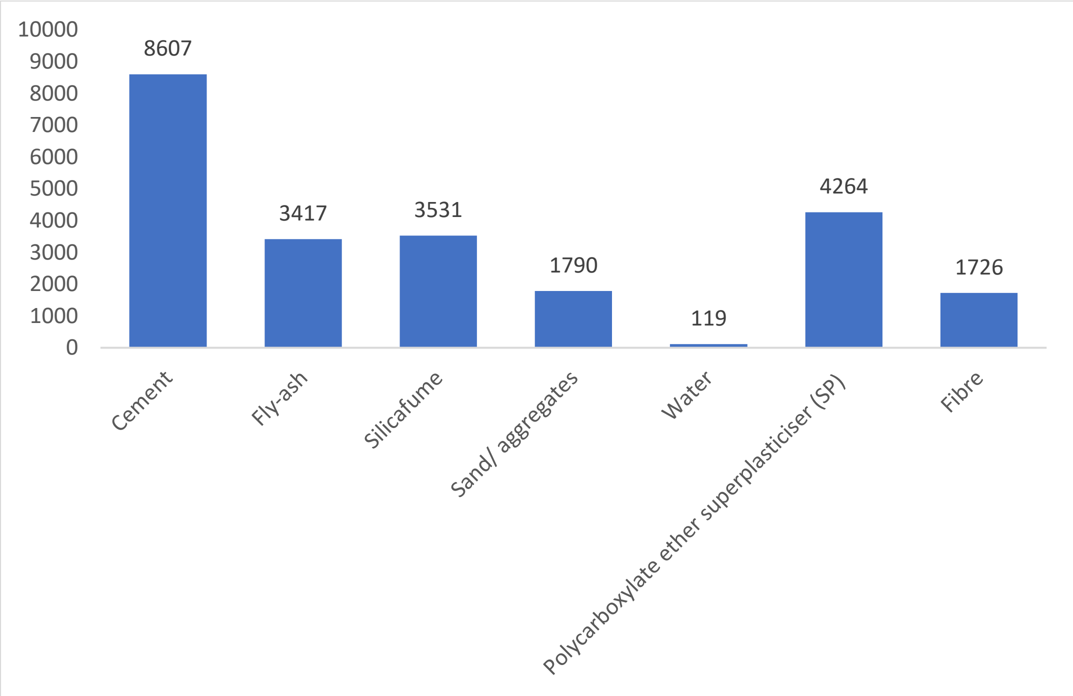


Figure 4-15 Material Cost for Scenario 3: Standard 3D Printed Villa.

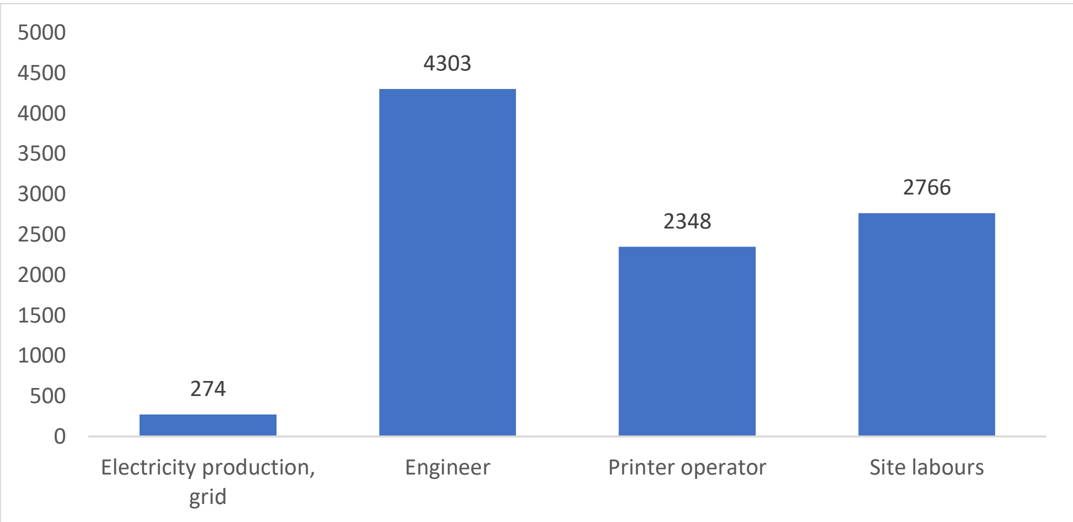


Figure 4-16 Construction Cost for Scenario 3: Standard 3D Printed Villa.

- 3DP Innovative villa

The results for the material cost for the Innovative 3D printed villa show that the 3D printing concrete mix had the highest impact on the cost at 21,154 SAR (Figure 4-17) For the construction cost, the salary of labourers and engineers had the most increased cost at 8, 071 SAR out of 8,296 SAR (Figure 4-18) .

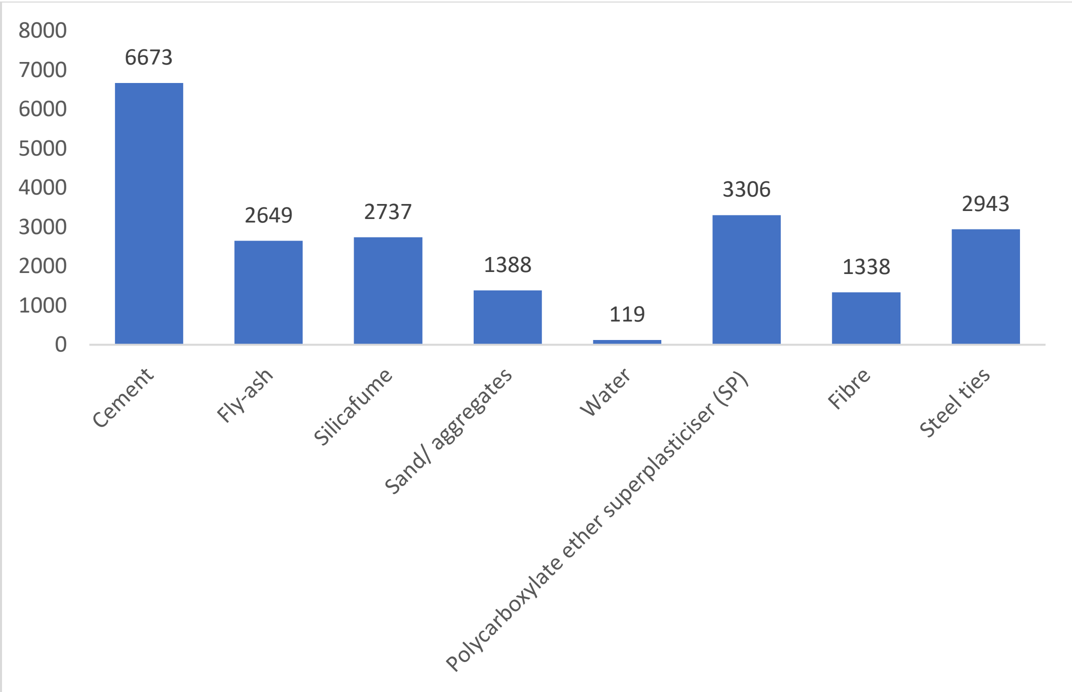


Figure 4-17 Material Cost for Scenario 4: Innovative 3D Printed Villa.

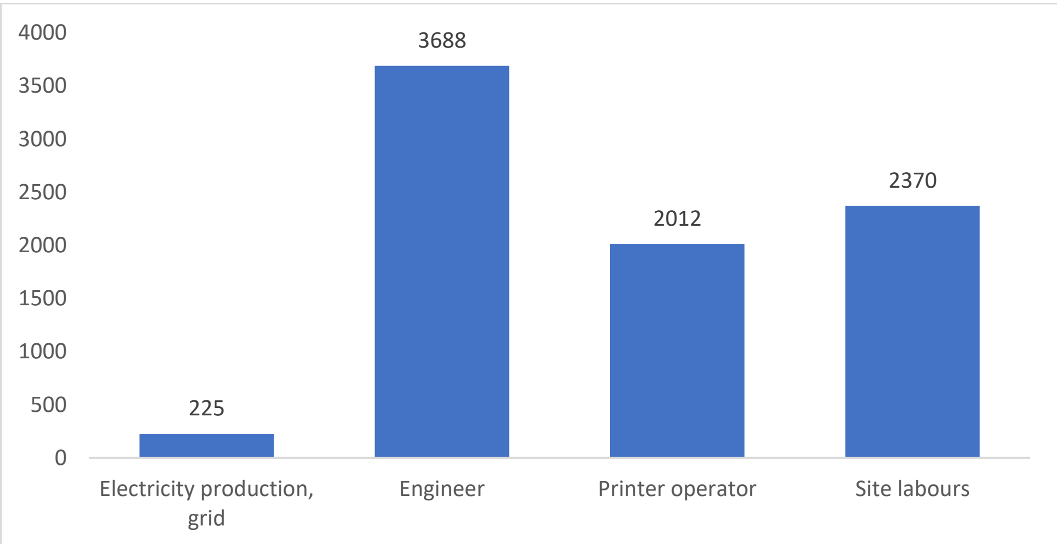


Figure 4-18 Construction Cost for Scenario 4: Innovative 3D Printed Villa.

4.4. Chapter Summary

This chapter has presented the results of the life cycle assessment (LCA) and economic analysis of the comparison of conventional and 3D printing technology construction methods. The evaluation was done on a one-storey villa in Al Khobar, Saudi Arabia, with four different construction methods. For LCA analysis, the environmental impact assessment was done for each scenario separately, after which all the results were compared. Furthermore, a sensitivity analysis was applied to assess the changes in the environmental impact for each scenario when changing the structural system or the used materials. The results revealed that 3D printing technology construction methods had a better environmental impact than conventional construction methods. The results also showed that the best performing scenarios regarding the impact on the environment are as follows: innovative 3DP villas, standard 3DP villas, precast villas, and conventional villas.

In all scenarios reinforcing steel, concrete mix and ceramic tiles had the highest environmental impact among all materials and processes. The sensitivity analysis unveiled that changing the foundation system from a raft foundation to an isolated foundation will have a better impact on the environment in the first scenario. Additionally, the change of ceramic tiles to epoxy floor paint in the other scenarios enhanced the environmental impact. After comparing the machinery used in 3D printing technology (robot and gantry), the results suggest that there is not that much of a difference regarding the environmental impact, but the difference will be observed at the time of printing.

Regarding the economic analysis, the 3D printing technology construction methods had a better economic impact than the conventional construction methods. The results demonstrated that the best performing scenario regarding the economic aspect in the four scenarios is as follows: innovative 3DP villas, standard 3DP villas, conventional villas, and precast villas. The results determined that each scenario had a different material that had the highest impact on the material cost. In the first scenario (conventional villa) it was concrete masonry units (CMU) for the outside and inside walls. In the second scenario (precast villa) it was concrete mix and in the third and fourth scenarios (standard 3DP villa and innovative 3DP villa) it was 3D printing concrete mix. Additionally, it was observed in the construction cost that the highest impact on the cost came from labourers and the time of construction. The next chapter will present the results of an online questionnaire given to the professionals in the construction industry in Saudi Arabia to get their perspectives on adopting 3D printing as a new construction method.

Chapter 5: Results and Analysis of Professionals' Attitudes and Willingness Towards the Adoption of 3D printing Technology in The Construction Industry

5.1. Introduction.

The chapter represents the questionnaire survey analysis and outcomes that assesses the adoption of 3DP technology in the construction industry in Saudi Arabia. The chapter is designed as the following: Section 5.2., demographic characteristics of the participants, describes in percentage the participants' gender, age, profession and academic qualification, and the level of awareness of 3D printing technology in the construction industry. Section 5.3., testing each attribute independently, provides the participants' perceptions regarding the diffusion of innovations theory attributes. An analysis of the mean score ranking is presented for each attribute independent. Section 5.4., hypotheses testing, shows the hypothesis testing for each attribute, while Section 5.5. provides an overview of the findings and a conclusion.

5.2. Demographic Characteristics.

The demographic characteristics about the study's participants will be described in this section. The number and percentage of each participant will be presented and discussed as follows: gender, age, profession and academic qualification, work experience, and finally, the awareness of 3D printing technology in the construction industry.

- Gender

The evaluation of the demographic characteristics of the respondents revealed that a total of 384 males took a part in the survey, 13 females participated, and one person preferred not to say. This demonstrates that 96.5% of respondents are male, 3.3% are female and 0.2% choose not to say (Table 5-1).

Table 5-1 Participants' Gender.

Gender	N	Percentage
Male	384	96.5
Female	13	3.3
Prefer not to say	1	0.2
Total	398	100

- Age

The results of the data analysis suggest that the first category, 18–34 years, has the highest percentage of participation, 45.7%. The second age group, 35–49 years, came in second with 38.9%, while the age group, 50–64 years, came in third with 12.8%. The final age group of participants is those aged 65 and up, which accounted for 2.5% of the overall respondents (Table 5-2).

Table 5-2 Age of the Participants

Category	N	Percentage
18–34	182	45.7
35–49	155	38.9
50–64	51	12.8
65+	10	2.6
Total	398	100

- Profession and Academic Qualification

194 architects, representing 48.7% of the total respondents, and 204 civil engineers, representing 51.3% of the total respondents, participated in this survey (Table 5-3). The survey analysis also discovered that 65.1% of the participants have a bachelor's degree, 27.1% have a master's degree and 7.8% have a PhD degree. This finding indicated that participants with a bachelor's degree were more likely to participate in the study than those with other degrees (Table 5-4).

Table 5-3 Participants' Profession.

Profession	N	Percentage
Architect	194	48.7
Civil Engineer	204	51.3
Total	398	100

Table 5-4 Academic Qualification.

Category	N	Percentage
Bachelor’s degree	259	65.1
Master’s degree	108	27.1
PhD degree	31	7.8
Total	398	100

- The Level of Awareness of 3D Printing Technology in the Construction Industry

The outcomes from the survey analysis indicate that a total number of 30 participants, that represents 7.5% of the total respondents, are not aware of the 3D printing technology in the construction industry. 61 participants, representing 15.3% of the total respondents, were aware of 3D printing technology in the construction industry for a year. Furthermore, 225 of the participants, representing 56.6% of the total respondents, were aware of 3D printing technology in the construction industry for the past 5 years. Finally, 82 participants, representing 20.6% of respondents, were aware of 3D printing technology in the construction industry for longer than 5 years ago. This outcome implies that the majority of the participants are aware of the 3D printing technology in the construction industry (Table 5-5).

Table 5-5 Level of Awareness of 3D Printing Technology in the Construction Industry.

Responses	N	Percentage
I was not aware	30	7.5
Up to 1 year ago	61	15.3
In the past 1 to 5 years	225	56.6
More than 5 years ago	82	20.6
Total	398	100

5.3. Testing Each Attribute Independently.

This section has been organised to thoroughly examine each of Rogers's five innovation attributes, which served as the study's theoretical framework. As mentioned in Chapter 3, Section 3.3.3., each attribute (Relative Advantage, Complexity (Ease to use), Compatibility, Observability and Trialability) will be analysed using mean score ranking. The ranking is done to indicate the most important item in each attribute.

- Relative Advantage

This attribute is meant to evaluate the participants' perception of the advantages of 3D printing technology construction methods over conventional construction methods. According to Rogers (2003), this perception will impact the adoption of a particular invention, such as 3D printing technology construction. This led to the use of eight items to assess this attribute. Moreover, these items investigated the perception of participants concerning the ability of 3D printing technology construction methods to produce more complex shapes than conventional construction methods, the ability of 3D printing technology construction methods to reduce construction costs more than conventional construction methods, the ability of 3D printing technology construction methods on reducing material waste more than conventional construction methods, the ability of 3D printing technology construction methods on reducing overall construction life cycle environmental impacts more than conventional construction methods, the ability of 3D printing technology construction methods on reducing time more than conventional construction methods, the ability of 3D printing technology construction methods on improving construction quality more than conventional construction methods, the ability of 3D printing technology construction methods on enhancing construction productivity more than conventional construction methods and the ability of 3D printing technology construction methods on improving the functionality of the finished building more than conventional construction methods.

The analysis results reveal that the ability of 3D printing technology construction methods to reduce time more than conventional construction methods is the most important item with the highest mean score of 4.19. Next in the ranking was the ability of 3D printing technology construction methods on reducing material waste more than conventional construction methods, with a mean score of 4.17, which was not much different from the mean score of the first item. The mean scores of both the ability of 3D printing technology construction methods on enhancing construction productivity more than conventional construction methods and the ability of 3D printing technology construction methods to produce more complex shapes than conventional construction methods were statistically indifferent (3.88 and 3.87, respectively). Furthermore, the ability of 3D printing technology construction methods on improving construction quality more than conventional construction methods ranked fifth with a mean score of 3.74. The ability of 3D printing technology construction methods on reducing overall construction life cycle environmental impacts more than conventional construction methods ranked sixth with a mean score of 3.61. The ability of 3D printing technology construction methods to reduce construction costs more than conventional construction methods ranked seven, with a mean score of 3.47. Finally, the ability of 3D printing technology construction methods on improving the functionality of the finished building more than conventional construction methods ranked last, with a mean score of 3.44 (Table 5-6).

Table 5-6 Relative Advantage of 3D Printing Technology in Construction.

Relative Advantage	Mean	Standard Deviation	Std. Error Mean	Likert Scale Score	Rank
3D printing technology reduces the construction time of a building.	4.19	0.861	0.043	Strongly agree	1
3D printing technology reduces construction material waste.	4.17	0.844	0.042	Strongly agree	2
3D printing technology enhances construction productivity.	3.88	0.832	0.042	Agree	3
3D printing technology produces more complex shapes than other construction methods.	3.87	1.009	0.051	Agree	4

Relative Advantage	Mean	Standard Deviation	Std. Error Mean	Likert Scale Score	Rank
3D printing technology improves the quality of construction.	3.74	0.956	0.048	Agree	5
3D printing technology lowers overall construction life cycle environmental impacts.	3.61	0.91	0.046	Agree	6
3D printing technology reduces the construction cost of a building.	3.47	1.025	0.051	Agree	7
3D printing technology improves the functionality of the finished building.	3.44	0.992	0.05	Agree	8

- Complexity (Ease of use)

This attribute aims to investigate the participants' perceptions of the complexity (ease of use) of 3D printing technology in construction. This attribute was tested by using the following six items to explore the participants perception concerning: the easiness of finding experts to discuss and share their experience and knowledge of 3D printing technology, the easiness of understanding and using 3D printers, the easiness of finding employees who can operate 3D printers, the easiness and the straightforward setting up of 3D printing technology, the adoption of 3D printing technology to improve collaboration among architects, engineers, consultants and contractors and the easiness of the process of implementing 3D printing technology.

The investigation shows that the adoption of 3D printing technology to improve collaboration among architects, engineers, consultants, and contractors is the most important item with the highest mean score of 3.71. Next in the ranking was the easiness of understanding and using 3D printers with a mean score of 3.16, which was not much different from the mean score of the easiness and straightforward setting up of 3D printing technology with a mean score of 3.10. Moreover, fourth in raking was the easiness of the process of implementing 3D printing technology, with a mean score of 2.91. Finally, the mean scores of both the easiness of finding experts to discuss and share their experience and knowledge of 3D printing technology and the easiness of finding employees who can operate 3D printers were statistically indifferent, with mean scores of 2.40 and 2.48, respectively (Table 5-7).

Table 5-7 Complexity (Ease of use) of 3D Printing Technology in Construction.

Complexity	Mean	Standard	Std.	Likert	Rank
Adopting 3D printing technology improves collaboration among architects, engineers, consultants and contractors	3.71	0.915	0.046	Agree	1
3D printing technology is easy to understand and use	3.16	1.016	0.051	Agree	2
Setting up 3D printing technology is clear and straightforward	3.10	1.000	0.05	Agree	3
Implementing 3D printing technology is a simple process	2.91	1.020	0.051	Neutral	4
It is easy to find experts to discuss and share their experience and knowledge of 3D printing technology	2.48	1.078	0.053	Neutral	5
Finding employees who can operate 3D printers is easy	2.4	1.133	0.570	Neutral	6

- Compatibility

This attribute aims to find out how participants felt about the compatibility of their use of 3D printing technology in construction. This attribute was assessed using six items. These items discovered the perception of participants concerning the intention of the participants' workplace to provide seminars and workshops on 3D printing technology, the compatibility of 3D printing technology to the construction site environment, the compatibility of 3D printing technology materials with conventional construction materials, the compatibility and flexibility of 3D printing technology to print various sizes of objects for different construction needs, the workplace of the participants have already investigated 3D printing technology and the consistency of 3D printing technology to the needs of the participants' workplace needs.

The analysis findings suggest that the compatibility and flexibility of 3D printing technology to print various sizes of objects for different construction needs is considered the most important item with the highest mean score of 3.55. Next in the ranking was the compatibility of 3D printing technology to the construction site environment, with a mean score of 3.27. Additionally, the consistency of 3D printing technology to the needs of the participants' workplace ranked third, with a mean score of 3.10. The compatibility of 3D printing technology materials with conventional construction materials ranked fourth, with a mean score of 2.90. The participants' workplace has already investigated 3D printing technology was next, with a mean score of 2.47. Finally, the intention of the participants' workplace to provide seminars and workshops on 3D printing technology achieved the lowest mean score of 2.45 (Table 5-8).

Table 5-8 Compatibility of 3D Printing Technology in Construction.

Compatibility	Mean	Standard Deviation	Std. Error Mean	Likert Scale Score	Rank
3D printing technology has the flexibility to print various sizes of objects for different construction needs	3.55	0.915	0.051	Agree	1
3D printing technology is compatible with a construction site environment	3.27	0.972	0.049	Agree	2
3D printing technology is consistent with the needs of my workplace	3.10	1.118	0.056	Agree	3
The materials used in 3D printing technology are compatible with conventional construction	2.90	0.980	0.049	Neutral	4
My workplace has already investigated 3D printing technology	2.47	1.235	0.062	Neutral	5
My workplace intents to provide seminars and workshops on 3D printing technology	2.45	1.152	0.580	Neutral	6

- Observability

This attribute is used to determine how participants felt about their opportunities and their ability to observe the operations of 3D printing technology in construction. This attribute was measured using six items. These items studied the perception of participants regarding their observation of how 3D Printing technology gives greater control over work quality parameters, produces aesthetically more pleasing results, is more economical than conventional construction methods, is faster than traditional construction, is more effective than traditional construction and offers a competitive advantage to a company.

The analysis findings discovered that the participant's observation of how 3D printing technology is faster than traditional construction was considered the most important item with the highest mean score of 4.06. Next in the ranking was the participants' observation of how 3D Printing technology gives greater control over work quality parameters, with a mean score of 3.83. Furthermore, third in the ranking was the participants' observation of how 3D printing technology offers a competitive advantage to a company, with a mean score of 3.67. The participants' observation of how 3D printing technology is more economical than conventional construction methods ranked fourth, with a mean score of 3.56. The participants' observation of how 3D printing technology is more effective than traditional construction ranked fifth, with a mean score of 3.49. Finally, the participants' observation of how 3D printing technology produces aesthetically more pleasing results achieved the lowest mean score of 3.41 (Table 5-9).

Table 5-9 Observability of 3D Printing Technology in Construction.

Observability	Mean	Standard	Std.	Likert	Rank
I have observed how 3D Printing technology is faster than traditional construction	4.06	0.81	0.041	Strongly agree	1
I have observed how 3D Printing technology gives greater control over work quality parameters	3.83	0.835	0.042	Strongly agree	2
I have observed how 3D printing technology offers a competitive advantage to a company	3.67	0.939	0.047	Agree	3
I have observed how 3D printing technology is more economical than conventional construction methods	3.56	0.976	0.049	Agree	4
I have observed how 3D Printing technology is more effective than traditional construction	3.49	0.972	0.049	Strongly agree	5
I have observed how 3D printing technology produces aesthetically more pleasing results	3.41	1.109	0.056	Agree	6

- Trialability

This attribute aims to explore the participants' perceptions concerning their intention to try out 3D printing technology in construction. This attribute was tested using the following six items: there are many hurdles to overcome before the participants' workplace could experiment with 3D printing technology, the participants' firm intends to experiment with 3D printing technology in the next 5 years, the participants' workplace would need to try the process and technology before deciding whether to use 3D Printing technology in construction or not, 3D printing technology building codes and regulations should be accredited before trying the technology, the participants' workplace would adopt 3D printing technology only if other companies or firms started using it and the ability to try 3D printing technology before adoption provides the possibility of risk reduction.

The outcome of the investigation indicates that the most important item was 3D printing technology building codes and regulations should be accredited before trying the technology, with the highest mean score of 4.28. Next in the ranking was the participants' workplace would need to try the process and technology before deciding whether to use 3D Printing technology in construction, which was not much different compared to the first item with a mean score of 4.21. Furthermore, with a mean score of 4.13, the ability to try 3D printing technology before adoption provides the possibility of risk reduction came third in the ranking. The participants' view about there being many hurdles to overcome before their workplace can experiment with 3D printing technology ranked fourth, with a mean score of 3.98. Next, the participants' workplace would adopt 3D printing technology only if other companies or firms started using it ranked fifth with a mean score of 3.66. Finally, the participants' firm intention to experiment with 3D printing technology in the next 5 years achieved the lowest mean score of 3.09 (Table 5-10).

Table 5-10 Trialability of 3D Printing Technology in Construction.

Trialability	Mean	Standard Deviation	Std. Error Mean	Likert Scale Score	Rank
3D printing technology building codes and regulations should be accredited before trying the technology	4.28	0.872	0.044	Strongly agree	1
Before deciding whether to use 3D Printing technology in construction or not, my workplace would need to try the process and technology	4.21	0.879	0.044	Strongly agree	2
The ability to try 3D printing technology before adoption provides the possibility of risk reduction	4.13	0.851	0.043	Strongly agree	3
There are many hurdles to overcome before my workplace can experiment with 3D printing technology	3.98	0.885	0.044	Strongly agree	4
My workplace would adopt 3D printing technology only if other companies or firms started using it	3.66	1.028	0.052	Strongly agree	5

Trialability	Mean	Standard Deviation	Std. Error Mean	Likert Scale Score	Rank
My firm will experiment with 3D printing technology in the next 5 years	3.09	1.055	0.053	Agree	6

5.4. Hypotheses Testing

The Sign test was utilised to examine the study hypotheses, which is used to examine the median difference between the paired samples. The first hypothesis, “Relative advantage will have a significant positive effect on 3D printing technology adoption”, was supported by this test. The results show that the *P-value* is 0.008, which is < 0.05. The second hypothesis, “Complexity has a significant positive impact on 3D printing technology”, was also supported. The results indicate that the *P-value* is 0.000, which is < 0.05. In addition, the third hypothesis, “Compatibility will have a significant positive effect on 3D printing technology adoption,” was also supported. The results show that the *P-value* is 0.001, which is < 0.05. The fourth hypothesis, “Observability will have a significant positive effect on 3D printing technology adoption”, was supported too. The results reveal that the *P-value* is 0.024, which is < 0.05. Finally, the fifth hypothesis, “Trialability will have a significant positive effect on 3D printing technology adoption,” was also supported. The results indicate that the *P-value* is 0.000, which is < 0.05 (Table5-11).

Table 5-11 Hypothesised Structural Model Testing.

Attribute	Sample median	Sign test (*P-value*)
Relative Advantage	3.71	0.008
Complexity	2.83	0.000
Compatibility	2.83	0.001
Observability	3.66	0.024
Trialability	4	0.000

5.5. Chapter Summary.

This chapter represented the questionnaire survey's analysis and outcomes that assessed the adoption of 3DP technology in the construction industry in Saudi Arabia. The findings indicated that a higher number of participants are male. The majority of the participants in the survey are between the ages of 18 and 34. It was also seen that a more significant percentage of the respondents (65.1%) have a bachelor's degree. 56.6% of the participants were aware of the 3D printing technology in the construction industry for the past 5 years, while 20.6% were aware of the 3D printing technology in the construction industry for more than 5 years. This indicates that the construction industry has a high level of awareness of 3D printing technology in the construction industry.

The results of the analysis of each of Roger's attributes revealed that in relative advantage, 3D printing technology construction methods have a higher ability in saving construction time than conventional construction methods were considered to be the most important item with the highest mean score of 4.19. In complexity (ease of use), the adoption of 3D printing technology will have the ability to enhance collaboration among architects, engineers, consultants, and contractors was the most important item with the highest mean score of 3.71. Furthermore, with regards to compatibility, 3D printing technology has the compatibility and flexibility to print various sizes of objects for different construction needs was the most important item with the highest mean score of 3.55. The participants' observation of how 3D printing technology is faster than traditional construction was considered the most important item with the highest mean score of 4.06, in observability. Finally, in trialability, 3D printing technology building codes and regulations should be accredited before trying the technology was considered the most important item, with the highest mean score of 4.28.

The results of testing the five hypotheses for Roger's attributes were supported, with *P-values* for all hypotheses as follows: 0.008, 0.000, 0.001, 0.024 and 0.000. The next chapter will present the discussion and findings of the results from the previous chapters to identify the feasibility of adopting 3D printing technology as a new construction method in Saudi Arabia. The discussion chapter will also compare the obtained data from this study with the presented data in the literature review.

Chapter 6: Discussion

6.1. Introduction

The aim of this chapter is to present and discuss the main findings of this research study. The results were previously mentioned in depth in Chapters 4 and 5 in relation to the research objectives in Chapter 1. This chapter is divided into four main sections. Section 6.2. revisits the research aim, objectives, questions, the study's methodological approach and the purpose of the study. Section 6.3. introduces the discussion of research findings. This section covers the environmental aspect (LCA) of 3D printing technology vs conventional construction methods, the economical aspect of 3D printing technology vs conventional construction methods and the level of adoption of 3D printing technology among professionals in relation to the Diffusion of Innovations Theory (DIT) framework. Furthermore, Section 6.4. will present the findings of Saudi Arabia's housing industry. This section will discuss and link the findings of this research to the Saudi housing industry's challenges and the government's initiatives. Section 6.5. demonstrates the key research findings of this study. Finally, Section 6.6. presents a summary of the chapter.

6.2. Revisiting the Research Aim, Objectives, Questions, the Study's Methodological Approach and the Purpose of the Study

As discussed in Chapter 1, this study aims to investigate the potential of leveraging 3D printing technologies as a new construction method in Saudi Arabia. This investigation will be based on a comparison between 3D printed technology and conventional construction methods with regard to the environmental, economic, and professional aspects. Moreover, to accomplish the aim, seven objectives were established towards accomplishing the research aim. These are as follows:

1- Survey the literature to assess the current construction methods used in Saudi Arabia.
2- Survey the literature to investigate 3D printing technology construction methods for large-scale buildings.
3- Survey the literature to explore the theories of adopting new technologies.
4- Survey the literature to assess the importance of sustainability along with the existing environmental performance methods for buildings.

5- Use LCA methods to evaluate the environmental impact of conventional and 3D printing technology methods.
6- Perform a cost analysis to assess the economic aspect of conventional and 3D printing technology methods.
7- Conduct a questionnaire to investigate the professionals' attitude and willingness towards adopting 3D printing technology construction methods as a new construction method in Saudi Arabia.

Based on the objectives stated above, three research questions were established to provide a guide to the research and fulfil the aim and objective of this research. These questions are presented as follows:

1- What is the difference in the environmental impact between 3D printed technology and conventional houses in Saudi Arabia?
2- What is the difference in the economic impact between 3D printed technology and conventional houses in Saudi Arabia?
3- Will 3D printing technology be accepted as a new construction method among the professional community in Saudi Arabia?

After reviewing the literature review and the research methodology, quantitative research methods were adopted to examine the adoption of 3D printing technology construction methods in Saudi Arabia. This was done by conducting the life cycle assessment, analysing the economics, and adopting the diffusion of innovations theory framework.

As stated in Chapter 1, the purpose of this study is to assess the adoption of 3D printing technology as a new construction method in Saudi Arabia from environmental, economic, and professional aspects. A person could question the relationship between the environmental, economic, and professional aspects; the answer to this question is that all these aspects will affect the adoption of 3D printing technology as a new construction method in Saudi Arabia and will enhance the sustainability of the housing industry. So, there is a need to investigate each aspect separately to determine which aspect may need more investigation if it was not accepted. The discussion of the research's findings, included in Section 6.3. below, is focused on how each of the research questions was answered.

6.3. Discussion of Research Findings

This research was conducted with proper attention to the three research questions established in an effort to accomplish the study's aim and objectives. The research outcomes are discussed in relation to the research questions. The research questions are covered in the subsections below:

6.3.1. The Environmental Aspect (Life Cycle Assessment) of 3D Printing Technology vs Conventional Construction Methods

The results of this study generally align with several other studies applied in the construction sector (Agustí-Juan and Habert 2017; Mohammad et al. 2020; Agustí-juan et al. 2017; Weng et al. 2020), which indicated that the environmental performance of 3D printing technology construction methods was better than that of conventional construction methods. Weng et al. (2020), for example, stated that constructing a prefabricated bathroom unit with 3D printing technology will reduce the CO_2 emission by 85.9% and energy consumption by 87.1%. Previous studies were done on a small scale; Agustí-Juan and Habert (2017) conducted their study on 1 m^2 of a concrete floor structure, Mohammad et al. (2020) performed their study on a section of 1 m^2 of an external load-bearing wall, Weng et al. (2020) performed their study on a prefabricated bathroom unit (L: 1620 mm; W: 1500 mm; H: 2800 mm), and Agustí-juan et al. (2017) conducted their study on 1 m^2. In contrast, the previous studies were done on one element of a building whereas this study was done on a large scale, with the assembly of more than one element in the building. Therefore, comparing the results of this study to the previous studies will not be accurate as the difference in scale could affect the comparison (Alhumayani et al. 2020).

As presented in Section 3.3.1. in Chapter 3, the LCA was performed to compare the environmental performance of a villa with four different construction scenarios. The first two scenarios, which represent the conventional techniques, are the conventional villa and precast villa, whereas the third and the fourth scenarios, which represent the 3D printing technology techniques, are the 3D printing standard villa and the 3D printing innovative villa. The analysis of the results demonstrated that the two conventional techniques had a higher environmental performance than the two techniques of 3D printing technology, especially in the first scenario (conventional villa), which had the highest environmental impact. This is because of the significant quantity of reinforcing steel and concrete, both of which are significant contributors to greenhouse gas emissions (GHG) (Fennell et al., 2021; Habert et al. 2013), particularly in the category of global warming, which is the category in which they are the most significant factor (European-Commission 2017). Furthermore, the findings suggest that even with the high percentage of cement in the 3D printing concrete mix, the calculation of SimaPro points to the advantages of 3D printing construction methods over conventional construction methods due to the use of less amount of cement. Another reason is that 3D printing techniques does not require the use of reinforced steel or formwork (CyBe, 2019), unlike conventional techniques that require them. Also, the amount of waste in 3D printing there is less compared to the conventional technique (Xia and Sanjayan 2016).

As presented in Chapter 4, the environmental performance comparison of the two conventional techniques shows that the precast villa has better environmental performance (0.3%) than the conventional villa, which indicates that the environmental performance of the conventional construction techniques does not have a significant environmental difference. Also, as presented in Chapter 4, an innovative 3D printed villa had a better environmental performance than the standard 3D printed villa by 3%. This is due to the reduced amount of 3D printed concrete used in the walls, as the 3D printed concrete mix will impact the structured walls environmental performance (Alhumayani et al. 2020). This illustrates that an increase in the innovation in the design of 3D printed houses can provide further opportunities for enhancing and reducing the environmental impact. Moreover, it was found that using the robotic arm or the gantry system in 3D printing construction will not significantly affect the building's environmental performance. The effect will be observed at the time of construction due to the limitation of the distance the robotic arm can reach during the printing process, where the gantry system could cover an area up to 300 m^2 (Delgado Camacho et al. 2018; COBOD 2019). Nevertheless, the robotic arm moves in six axes and the gantry system works with three axes, giving the robotic arm more flexibility for the work and taking less space (Delgado Camacho et al. 2018).

The sensitivity analysis for this study revealed that when changing the foundation type on the conventional house from a raft foundation to an isolated foundation, its environmental impact will improve. This demonstrates that isolated footing is better environmentally but, the issue is that not every house could be constructed with an isolated foundation due to the properties of the land. On the other hand, precast villas, 3D printing standard villas and 3D printing innovative villas had ceramic tiles as the third-highest contributor after reinforcing steel and concrete mix. Reinforcing steel and concrete mix could not be changed due to structural reasons. So, ceramic tiles were changed to epoxy floor paint. This change reduced the environmental impact, which implies that other options could also help the flooring performance. In the end, it could be stated that the 3D printing technology construction techniques have better environmental performance than conventional construction techniques.

6.3.2. The Economical Aspect of 3D Printing Technology vs Conventional Construction Methods

From an economic aspect (cost analysis), the results of this study align with the former studies concerning the economic benefits of the 3D technology construction method when compared to conventional construction methods. The results of Weng et al. (2020) confirmed that the 3D printing technology construction method will reduce the cost of construction by 25.4 %. Han et al. (2021) also conducted a study to examine the economic advantage of 3D printing technology when compared to traditional cast-in-situ. The study was performed on a hypothetical concrete cylindrical-silo model that contains of a conical top and an annular wall. Moreover, the study determined that 3D printing method provides a number of advantages over the conventional cast-in-situ technology.

The originality of this study is comparing more than one technique in both 3D printing technology and conventional construction methods. Moreover, the findings suggest that 3D printing technology excelled over conventional methods with the number of labourers required in the construction process being reduced by more than 90%, and prior studies support this for the huge saving of labour in the 3D printing technology (Geneidy et al. 2019; Chen & Yossef 2015; Hager et al. 2016; Nadal et al. 2017). This is due to the avoidance of formwork usage and higher automation in 3D printing technology (Weng et al. 2020). Additionally, when analysing the construction cost, it was observed that 3D printing technology is better than the conventional construction methods, especially in the precast construction technique. This is due to the high number of labourers needed in the factory for preparing the formwork (Han et al. 2021). This study was conducted in the Saudi Arabian context, which has a relatively minimum wage for the workforce compared to other countries (International Labour Organization 2021). Therefore, the labour cost should be adjusted accordingly on a case-by-case basis depending on the country (Weng et al. 2020).

It wasn't a surprise that 3D printing technology methods demonstrated a huge decrease in material cost compared to conventional methods. This can be explained also by the use of less formwork in 3D printing methods. It could be argued that for both the conventional techniques, formwork will be used on more than one project, so its cost will not be a big issue. However, this argument will limit the customers to one or two designs as some customers may ask to have a special and unique design for their houses.

Moreover, not having formwork will give 3D printing technology the ability to produce more than one building design. Another reason for 3D printing technology methods to have a better material cost than conventional methods is that in the conventional method, more than one type of material is used to construct the wall, such as concrete mix, concrete masonry units (CMU) for outside walls, mortar for concrete masonry units (CMU), steel bars and mortar for walls whereas in the 3D printing technology methods, 3D printing concrete mix alone or 3D printing concrete mix and steel bars are the only materials used.

Concerning the construction time, 3D printing technology methods could save more time on construction than conventional methods from 50-70% (Zhang et al. 2019; Agustí-Juan and Habert 2017). This claim was confirmed in this study, where the saving on the time of wall construction was more than 50%. It could be argued that the time of construction in the precast technique is almost the same as in 3D printing technology techniques. This could be justified by observing the time of preparing the formwork and the time of transporting the precast parts from the factory to the site. The transportation time will affect the time of the project to be ready, especially if the factory is far from the project location. It should be clarified that even with the cost and time advantage of 3D printing techniques, over conventional construction techniques, precast construction methods have lots of advantages compared to conventional construction methods such as the work in the precast method may be accomplished in a shorter period compared to the conventional construction method, the reduction of the number of scaffolding and formwork on site, and the cost-saving because of the reuse of formwork.

Additionally, in 3D printing technology, using a gantry system such as COBOD 2 will cause a drastic difference in the printing time compared to a robot arm such as the KUKA robot, as the gantry system could cover more area up to 300 m^2 than the robot arm, which is limited to 3 to 4 m^2 (Delgado Camacho et al. 2018; COBOD 2019). The continuous printing without stopping and moving the robot arm gives an advantage to the gantry system on timing even when using a linear track for the robot arm to move and a hydraulic system for it to reach higher places. At the end of the economic analysis, the researcher could state that in 3D printing technology construction methods, using less formwork, less labour and less material gives 3D printing technology an economic advantage compared to conventional construction methods.

6.3.3. The Level of Adoption of 3D Printing Technology Among Professionals in Relation to the Diffusion of Innovations Theory DIT Framework

This study used the diffusion of innovations theory (DIT) introduced by Rogers (1983) to examine the professionals' attitudes and willingness in adopting 3D printing technology in the construction industry in Saudi Arabia. After an extensive review of the related literature, 32 factors were theoretically justified and developed to be important in accepting 3D printing technology developed under the DIT model's attributes as discussed in Chapter 3. The results of this study regarding the awareness of 3D printing technology suggest a high level of awareness among architects and civil engineers in Saudi Arabia. Also, the level of awareness is different from one country to another. The study of Wu et al. (2018) demonstrated that in the Australian construction industry, the level of awareness is high but Geneidy et al.'s (2019) study stated that the Egyptian construction industry participants had a lack of knowledge and awareness of the technology.

Moreover, the word awareness could be a general word, and its assessment could be tricky. It could be just knowing about the technology, in general, or if they are experienced with it. In this study, the question was explicitly asked to know if the participants are aware that this technology is used in the construction industry. The previous studies didn't examine the correlation between the demographic characteristics and the adoption of the 3D printing technology (Calli & Busra Alma Calli 2020; Chatzoglou and Michailidou 2019), except Wang et al.'s (2016) research, which studied these relationships and found that there is a relationship with some characteristics and the adoption of 3D printing technology. A correlation test was done with each category of the demographic characteristics of gender, age, profession, and academic qualifications in this study. It was found that there isn't a significant correlation between any of the characteristics and the adoption of 3D printing technology.

Regarding the diffusion of innovations theory (DIT), five hypotheses were developed for this study, as shown in Chapter 2, to study which attributes will affect the adoption of 3D printing technology. The test of each hypothesis was found to be supported, as each attribute had a *P-value* < 0.05. The findings of this study don't agree with the findings from previous studies. Moreover, Marak et al. (2019) determined that relative advantage, trialability and complexity (ease of use) significantly affect the adoption of 3D printing technology. In contrast, observability and compatibility had a non-significant effect on the adoption. The findings from Chatzoglou and Michailidou (2019) also suggest that perceived usefulness, compatibility, intention to use and output usability significantly affect the adoption. In contrast, compatibility, relative advantage, job relevance, experience and ease of use were partially accepted. Since all five attributes have a significant positive relationship with the adoption of 3D printing technology, the mean score will determine the highest important attribute in the DIT model. The results indicate that trialability had the highest mean among most attributes affecting the adoption of 3D printing technology, followed by relative advantage, observability, complexity, and compatibility.

It makes sense that trialability came as the essential attribute in adopting 3D printing technology, which goes to show that even architects and civil engineers in Saudi Arabia have a high level of awareness about the technology and its benefits. However, they still want to experiment with the technology and understand its capabilities before they decide to adopt it. Moreover, it was essential to understand what are the most critical factors that affect each attribute. In relative advantage and observability, participants think that time is the most important factor among the other factors in the adoption of 3D printing technology. This implies that there is an issue with the current construction methods, and there is a need for improvement, which is proven in the 3D printing technology (Nadal et al. 2017). In complexity (ease of use), the participants think that 3D printing technology improves collaboration among architects, engineers, consultants, and contractors.

Nevertheless, new technologies enhanced the collaboration among the project parties even before 3D printing technology, such as building information modelling BIM (Azhar 2011). In compatibility, the participants think that printing various sizes of objects for different construction needs is an important factor in the adoption of

3D printing technology. This reveals that in the current construction methods, the manufacturing of various sizes is costly, needs more specialised labour or takes time due to transportation. Finally, in trialability, the participants believe there is a need to have building codes and regulations for 3D printing technology in the construction sector. The quality and regulations standards in the construction sector weren't developed for 3D printing technologies, which may delay the adoption of the technology (Strauss 2013). The participants' views in this study regarding the need for building codes and regulations aligned with the views of the Australian construction industry's views (Wu et al. 2018). After assessing the professionals' attitude and willingness towards adopting 3D printing technology construction methods as a new construction method in Saudi Arabia, it can be stated that according to the diffusion of innovations theory (DIT), 3D printing technology will be accepted as a new construction method in Saudi Arabia.

6.4. Mapping the Findings with Saudi Arabia Housing Industry

Numerous challenges to the housing industry have occurred in Saudi Arabia over the last two decades, and it is critical that they are addressed effectively (Alqahtany & Bin Mohanna, 2019). In Chapter 2, Section 2.3.5., the researcher identified that there are a few challenges the construction industry in Saudi Arabia is facing, including population growth and high demand for housing, current construction methods issues and the lack of using modern methods, high cost of construction and environmental challenges. Also, in Section 2.3.6., Saudi Arabia Vision 2030 has presented more than one initiative that could help in improving the housing sector in Saudi Arabia. These initiatives are the Housing Program (Sakani), Sustainable Building Initiative and Building Technology Stimulus Initiative (BTSI).

- Housing Challenges in Saudi Arabia

a- Population Growth and High Demand for Housing

The Saudi population is estimated to be 35,013,414 million people and the growth rate is 1.7% (GaStat 2021). This is estimated to rise in the upcoming years to reach 41.3 million by 2030. The rapid rise of the population has led to high demand for houses (Ahmed et al. 2019; Mulliner and Algrnas 2018). Moreover, the Saudi government has made lots of efforts to cover the demand, but it did not go that far because of the high pressure of loans (Alqahtany 2019). The finding of this study proves that adopting 3D printing technology in the Saudi construction industry will help in decreasing the cost of construction, which will help the government in providing loans to the population to help them with constructing their homes. Also, SaudiGazette (2015) states that because of the expansion of the population, Saudi Arabia would need to build around 3 million houses by 2025. The ability to build this number of houses in a short time could be done using 3D printing because the findings of this study discovered that 3D printing technology construction methods are quicker compared to the conventional construction methods.

b- Current construction methods issues and the lack of involving recent methods

As discussed in Chapter 2, Section 2.3.5.3., the current conventional construction techniques have a multitude of issues, including the need for modification due to construction mistakes, labour inefficiency, insufficient time, an unqualified labour force and hiring an unqualified building contractor to design and construct the house (Assaf and Al-Hejji 2006; Ahmed et al. 2019). The findings of this research demonstrate that adopting modern methods such as the 3D printing technology construction method will help solve these issues. The advantage of 3D printing technology is that it is an automated process where the machine will do all the work without the interference of humans (Ngo et al. 2018b). Moreover, this advantage will help solve the issues of construction mistakes, unqualified labour force, hiring an unqualified building contractor, construction time and labour inefficiency. Also, the findings demonstrate the continuousness of the printing process will solve the issue of time more than the conventional technique.

c- High cost of construction

The high cost of housing construction in Saudi Arabia can be attributed to a variety of factors, including a lack of available labour, poor material standards, low design quality, frequent design modifications, ineffective on-site financial management, a lack of coordination, extended contract terms, higher material costs, and disagreements between workers on the job site (Saud and li 2020; Assaf et al. 2010).

Therefore, the adoption of 3D printing technology within the construction sector will have a beneficial influence on the cost of housing in Saudi Arabia. This is proven by the findings of this research as 3D printing technology utilises less material, generates less waste, saves time, uses fewer labourers, automates the process, enhances collaboration among the project team members and has the ability to construct a house according to the customer's preference without any additional cost.

d- Environmental Challenges

The majority of Saudi Arabia's environmental challenges are driven by the country's reliance on fossil fuels for growth and development (Demirbas et al. 2017). As presented in Chapter 2, Section 2.3.5.5., there are several industries in Saudi Arabia that are responsible for greenhouse gas (GHG) emissions (Alajmi 2021). The industries that demand the most energy demanding and contribute the most amount of GHG emissions are electricity and heat, transportation, manufacturing, and construction. Other industries also have a huge contribution, such as industry waste (Alajmi 2021). Furthermore, cement production, iron and steel production and cement industries accounted for 12% of the major sources that affected CO_2 emissions up till 2010 in Saudi Arabia.

The housing construction process is related to all the industries that contribute to greenhouse gas (GHG) emissions in one way or another. The findings of this study confirm that 3D printing technology construction methods will help reduce the greenhouse gas (GHG) emissions of housing construction as compared to the conventional construction methods in Saudi Arabia. The findings have determined that in 3D printing technology construction methods, there is no need for formwork, so this gives the 3D printing technology construction methods an advantage in saving materials, especially concrete and reinforced steel as these two materials contribute highly to greenhouse gas (GHG) emissions. Also, 3D printing technology has the ability to produce less waste compared to the conventional construction methods, which will help prevent material waste. The amount of material, number of labourers and construction elements are less in 3D printing technology construction methods compared to conventional construction methods, so the transportation process in

3D printing technology construction methods is less than in conventional construction methods, which will help reduce the impact of transportation to greenhouse gas (GHG) emissions in Saudi Arabia. It can be said in the end that the advantages of using 3D printing technology construction methods in Saudi Arabia as a new construction method will help reduce greenhouse gas (GHG) emissions in all the industries related to the housing construction industry.

Saudi Arabia Vision 2030 Initiatives

a- Sustainable Building Initiative

The Ministry of Housing launched the sustainable building platform with the goal of offering a wide variety of tools that contribute to the housing units' long-term viability. These tools or resources are building quality checks, prefab inspections, and sustainability assessment services. The findings of this study confirm that the 3D printing technology construction methods will help the achievement of this initiative by assuring a high quality of construction due to the automation of the process in 3D printing and the less interference of humans and decreasing the environmental impact of construction materials and waste.

b- Building Technology Stimulus Initiative (BTSI)

The Building Technology Stimulus Initiative (BTSI) was established by the Ministry of Housing to create future housing units that are sustainable, inexpensive, and smart using the newest construction technologies such as 3D printing technology. Also, this initiative was founded to help solve the affordable housing gap in Saudi Arabia. The objectives of this initiative are to decrease the time it takes to build residential units to increase housing output, make construction more of a source of value-added jobs for Saudi nationals, decrease the cost of building a single home to make it more affordable and improve the construction quality of residential dwellings. It was found that 3D printing technology will help this initiative to succeed as it will achieve the objectives of the BTSI Initiative by reducing the time of construction, reducing the cost of construction, adding new jobs to the housing construction industry, and improving the construction quality of buildings.

6.5. Key Research Findings

The key research findings on adopting 3D printing technology as a new construction method for houses in Saudi Arabia are summarised in (Table 6-1).

Table 6-1 Summary of the Key Research Findings.

Categories	Findings
Environmental Assessment	• 3D printing technology construction methods had a better environmental impact than conventional construction methods by 47% in all impact categories and 48.20% in global warming. • The environmental assessment of conventional construction techniques has revealed that there is not a significant environmental difference between the two techniques. • The conventional villa had the worst environmental impact among the four scenarios followed by the precast villa, then the 3D printed standard villa and finally, the 3D innovative villa. • The more innovative the design of 3D printed houses, the more opportunities there are to improve and reduce the environmental impact. • In all construction methods, reinforcing steel and concrete had the highest environmental impact among all materials. • Not using formwork gives 3D printing technology construction methods the ability to save materials, which will reduce the environmental impact.

Categories	Findings
	• Changing the foundation structure system from raft foundation to isolated footing will improve the environmental impact by 25% in all environmental categories and 29% in global warming. • In flooring, changing ceramic tiles to epoxy floor paint will improve the environmental impact by 20% in all environmental categories and 2% in global warming. • The environmental assessment of using the robotic arm or the gantry system in the construction of the 3D printing process has revealed that there is not a significant environmental difference between the two techniques.
Economic Assessment	• 3D printing technology construction methods had a better economic impact than conventional construction methods. • The number of labourers in the 3D printing technology construction methods is lesser compared to the conventional construction methods by more than 90%. • Not using formwork gives 3D printing technology construction methods an economic advantage in saving materials costs. • 3D printing technology construction methods produces less waste, which will affect the materials' cost. • Using more than one material in the wall construction in conventional construction methods will affect the cost. • In conventional construction methods, a conventional villa has a better economic impact than a precast villa. This is because of the number of labourers needed in

Categories	Findings
	the factory and the transportation of the constructed parts. • The construction process in 3D printing technology construction methods is an automated process, so the work will be done faster, which will save the construction time by more than 50%. • Not using formwork in 3D printing technology construction methods will give the technology the ability to construct more than one house with different designs without the need to prepare new formworks, which will affect the time and cost. • Using the gantry system for printing will affect the time of construction more than the robotic arm because of the limitation of the arm's reach.
Professionals Assessment	• More than 77% of the participants had a high level of awareness of 3D printing technology in the construction industry. • The testing of the hypothesis of the attributes of the diffusion of innovations theory (DIT) were all accepted with a *P-value* < 0.05. • The analysis of the DIT theory demonstrated that trialability came as the highest mean among most attributes influencing the adoption of 3D printing technology, followed by relative advantage, observability, complexity and finally compatibility. • In relative advantage and observability attributes, the participants believe that the ability of 3D printing technology to save time is the most important factor among the other factors for adopting 3D printing.

Categories	Findings
	• In complexity (ease of use), the participants believe that 3D printing technology having the ability to improve collaborations among architects, engineers, consultants, and contractors is the most important factor among the other factors for adopting 3D printing. • In compatibility, the participants believe that the ability of 3D printing technology to print various sizes of objects for different construction needs is the most important factor among the other factors for adopting 3D printing. • In trialability, the participants believe that having building codes and regulations for 3D printing technology in the construction sector is the most important factor among the other factors for adopting 3D printing.
The Impact of Adopting 3D Printing Technology as a New Construction Method in Saudi Arabia	• Adopting 3D printing technology in Saudi Arabia will help the population growth and high demand for housing in Saudi Arabia because of its ability to construct houses faster than the current construction methods. • Adopting 3D printing technology in Saudi Arabia will help solve the current construction methods issues (construction errors, labour inefficiency, insufficient time, an unqualified labour force and hiring an unqualified building contractor) because of the automated process in 3D printing technology where the machine will do all the work without the interference of humans, which will improve the quality of the buildings.

Categories	Findings
	• Adopting 3D printing technology in Saudi Arabia will help in solving the high cost of construction because of the ability of 3D printing technology to use fewer materials, generate less waste, save time, use fewer labourers, automate the process, enhance collaboration among the project team members and construct the house according to the customer's preference without any extra cost. • Adopting 3D printing technology will help improve the greenhouse gas (GHG) emissions in Saudi Arabia. This is done by not using formwork, using fewer materials, having less waste, and decreasing the effect of transportation. • Adopting 3D printing technology will help in accomplishing the objectives of the Sustainable Building Initiative by assuring high quality of construction due to the automation of the 3D printing process, decreasing the environmental impact of construction materials, and having less materials waste. • Adopting 3D printing technology will help in reaching the aim and objectives of the Building Technology Stimulus Initiative (BTSI) by decreasing the time of construction, adding new jobs for Saudi nationals, decreasing the cost of construction, and improving the quality of buildings.

6.6. Chapter Summary

This chapter emphasised the major findings of the study and discussed the results to provide an understanding of the feasibility of adopting 3D printing technology as a new construction method for houses in Saudi Arabia. This chapter started by revisiting the research aim, objectives, questions, the study's methodological approach and the purpose of the study. This chapter discussed the findings from the environmental, economic, and professional aspects. This chapter had established that 3D printing technology construction methods have a better environmental and economic impact than conventional construction methods. Also, the discussion of the professionals' attitudes revealed that the professionals are willing to adopt this technology in Saudi Arabia. After discussing all aspects, a mapping of the findings was linked to Saudi Arabia's housing industry. It was determined that adopting 3D printing technology will improve the housing challenges and help in achieving Saudi Vision 2030's initiatives. The next chapter will present the conclusion of this study.

Chapter 7: Conclusion

7.1. Introduction

This chapter aims to reveal how the research objectives were achieved. It presents the limitations of the study and the unique contribution to the body of knowledge. The chapter concludes with recommendations for future research and also for the construction industry, designers, decision-makers, and real estate developers.

7.2. The Achievement of Research Objectives

Seven objectives were investigated to accomplish the research aim. The research objectives were accomplished through the use of a quantitative research method. This section describes in detail how each of these objectives was achieved.

- Objective One

"Survey the literature to assess the current construction methods used in Saudi Arabia"

The current housing construction methods in Saudi Arabia were obtained through a thorough examination in Chapter 2. The literature review provided a clear insight of the development of the housing system in Saudi Arabia. Additionally, it also presented different types of contemporary houses in Saudi Arabia and how different construction methods are used over there. The literature also described the use of different materials in construction and their cost. The literature revealed that there are some challenges that are faced by the housing industry in Saudi Arabia such as population growth and high demand for housing, current construction methods issues and the lack of using modern methods, high cost of construction and environmental challenges. Also, the literature revealed that the Saudi government has announced a new vision called Saudi Vision 2030 that will adopt new technologies of construction to enhance the housing sector and reach the highest level of sustainability in the country.

- Objective Two

"Survey the literature to investigate 3D printing technology construction methods for large-scale buildings"

The investigation of 3D printing technology construction methods for large-scale buildings was achieved through a comprehensive investigation in Chapter 2. The literature provided an understanding of the definition of 3D printing technology and the different types of technologies and their principles. It also gave an insight into the used materials and the economic aspect of this technology. Additionally, it offered examples of 3D printed construction buildings from around the world to better understand how the field is working. The literature revealed that 3D printing technology is a promising method to be used in the construction of large-scale buildings due to its high capabilities in different aspects such as environmental, economic, and social.

- Objective Three

"Survey the literature to explore the theories of adopting new technologies"

The exploration of the theories of adopting new technologies was achieved through a thorough examination in Chapter 2. The literature introduced different theories that help adopt 3D printing technology in various sectors. Moreover, the literature revealed that four theories of adoption were used to assess the adoption of 3D printing technology. These theories are the Theory of Planned Behaviour (TPB), the Technology Acceptance Model (TAM), the Unified Theory of Acceptance and Use of Technology (UTAUT) and the Diffusion of Innovations Theory (DOI). The literature showed that most of these theories have demonstrated their efficiency in explaining and predicting a range of human behaviours in different settings. Also, some theories are similar and have an overlap where some others don't. The literature explored different studies that assessed the adoption of 3D printing technology in different sectors and revealed that there is a gap that needs to be fulfilled regarding the perception of architects and civil engineers, who are the individuals who deal with 3D printing technology directly in the construction industry.

After the review of different theories of adopting 3D printing technology, the Diffusion of Innovations Theory (DOI) was found to be the most appropriate theoretical model to use for this study as DOI was found to be a commonly accepted framework for evaluating the adoption and diffusion of new technologies. DOI explains the procedure of adopting the technology, for example, understanding the technology, the interest of adopting the technology, the intention of adopting the technology and finally adopting the technology. Also, DOI was used as a single framework in previous studies where the other theories had to be combined. Another reason for choosing DOI is that it serves the aim and objectives of the study (Chapter 3).

- Objective Four

"Survey the literature to assess the importance of sustainability along with the existing environmental performance methods for buildings"

The assessment of the importance of sustainability along with the existing environmental performance methods for buildings was achieved through a thorough exam in Chapter 2. The literature presented Sustainable Development and presented the three elements of Sustainability (economic, environmental, and social factors). The literature also revealed the efforts taken by the UN to introduce the principles, goals, and agenda to reach Sustainability in different areas. Moreover, the literature produced Sustainability in construction generally and how construction industry contributes significantly to environmental protection, economic growth, and social progress. Also, several initiatives were discovered to understand the principle of sustainability in the built environment for instance sustainable communities (social sustainability), sustainable architecture (ecological architecture) and sustainable building. The literature presented the influence of construction on the environment and how the life cycle of buildings affects greenhouse gas (GHG) emissions.

The literature revealed that there are three categories that assess the building's performance: Life cycle assessment (LCA) systems, Sustainable building rating and certification systems and Systems to manage the building's performance (Performance-Based Design). After a careful examination of different methods of building performance, Life-cycle assessment (LCA) was selected as the assessment method for this study. LCA was found to be the most suitable method for this study as LCA is capable of assessing the environmental impact of products and processes during the entire lifecycle of the building, which serves the objective of this study. Furthermore, other tools were also used to assess different aspects of a building, for instance, environmental impact assessment (EIA) concentrates on examining the environmental and economic impacts of projects, policies, or goals, as well as the overall project's environmental effect. It was found that LCA is a method that was accepted worldwide in many industries as well as the construction industry (Chapter 3).

- Objective Five

"Use the LCA method to evaluate the environmental impact of conventional and 3D printing technology methods"

The assessment of the environmental impact of conventional and 3D printing technology methods was achieved by using LCA as an assessment method. This study was done on an existing one-storey villa in Al Khobar City in Saudi Arabia (Chapter 3). The LCA study was done on the same villa in four scenarios. The first two scenarios utilised the conventional construction techniques, and the other two utilised the 3D printing construction techniques. Moreover, due to the current limited information concerning 3D printing technology in construction, this research adopted the cradle-to-gate approach. The outcomes of the LCA study demonstrated that 3D printing technology construction methods had a lower environmental effect than conventional construction methods. The findings also revealed that the innovative 3DP villa had the lowest environmental impact, followed by the standard 3DP villa, then the precast villa and finally the conventional villa (Chapter 4).

- Objective Six

"Perform a cost analysis to assess the economic aspect of conventional and 3D printing technology methods"

The assessment of the economic aspect (cost analysis) of conventional and 3D printing technology methods was achieved through conducting cost analysis for the internal and external walls for the same villa that was used in the LCA study again with the same four scenarios. The cost analysis was done in two phases: the materials cost and the construction cost. Additionally, the findings of the cost analysis demonstrated that 3D printing technology construction methods had a better economic impact than conventional construction methods. The findings also uncovered that the innovative 3DP villa had the most favourable economic impact, followed by the standard 3DP villa, then the conventional villa and finally the precast villa.

- Objective Seven

"Conduct a questionnaire to Investigate the professionals' attitudes and willingness towards adopting 3D printing technology construction methods as a new construction method in Saudi Arabia"

The investigation of the professionals' attitudes and willingness towards adopting 3D printing technology construction methods as a new construction method in Saudi Arabia was achieved through conducting a questionnaire with the professionals (Architects and Civil Engineers) who work in the construction industry in Saudi Arabia using the Diffusion of Innovations Theory (DOI) (Chapter 4). The outcomes of the study revealed that there is a high level of awareness among professionals concerning the use of 3D printing technology in the construction industry. Moreover, the findings demonstrated that after testing the attributes of DOI, the professionals agree that 3D printing technology will enhance the construction sector in Saudi Arabia from more than one aspect and it could be alleged that they are willing to adopt 3D printing technology in the Saudi construction industry.

7.3. Research Limitations

Several limitations were experienced by the researcher throughout the research process, which are summarised below:

- The LCA method has some limitations that can affect the results of the study such as lack of data accuracy, data availability, the effect of using different impact assessment methods and the clarification of results. In this research, lots of assumptions were made about the used trucks, fuel type, materials, and type of 3D printers. However, all the assumptions were consistent with the previous literature, public databases and LCA software databases. Furthermore, the provided data to the background systems in the SimaPro database are considered a limitation of this study. This is because the specifications of the materials and the impact method assessed vary from one country to another. For this study, all the specifications for the used materials and the used impact method were chosen from a category called rest of the world or globally, except for the electricity grid source where the chosen category was Saudi Arabia's electricity source grid. Also, the normalisation and weighting factors have been acquired from the European Commission Platform on Life Cycle Assessment because of the lack of information in the Saudi context.

- Due to the current limited information about 3D printing technology in construction, the system boundary of this research was cradle-to-gate.

- Due to the absence of codes and regulations for 3D printed house designs, the configuration of the design was done according to the literature and industry practice.

- At the beginning of the study, the researcher tried to contact the companies that produced and sold 3D printing concrete mixes to get the concrete mix specifications. However, these companies did not cooperate with the researcher, so the researcher had to rely on previous mixes from the literature.

- In the economic aspect of the study, the cost analysis was done on the internal and external walls for all four scenarios, except for the finishing phase, roof, and foundation cost. The finishing phase wasn't added because of the data availability as The General Authority for Statistics and the private sector do not provide an estimation of the finishing materials prices. Also, the finishing part of a building depends on the clients' desires and how much he/she wants to spend. The reason for excluding the cost of the roof and foundation is that the construction cost of these elements is relatively similar. Additionally, it must be stated that the cost of constructing the walls from the whole building cost doesn't represent a huge percentage of the construction cost so the final results might not give 3D printing technology the economic advantage.

- This research was carried out in the setting of Saudi Arabia, which has a relatively low minimum wage for its employees when compared to other nations. Therefore, the findings may want to be adjusted if the study were to be done in another country as the labourer's wages vary from one country to another.

- The professionals' study findings are only applicable in the setting in which they were conducted. Other professionals from other countries may have opposing viewpoints on the adoption of 3D printing technology in the construction sector. As a result, when attempting to generalise or apply the results of this research to other countries, the contextual differences should indeed be considered.

- The General Authority for Statistics does not provide the total number of civil engineers and architects that work in Saudi Arabia. So, the researcher calculated the sample size number for the questionnaire according to the registered architects and civil engineers in The Saudi Council of Engineers (SCE). One of the issues of the SCE is that they do not require the architects and civil engineers who work in the government and the military sector to register.

7.4. Contribution to the Body of Knowledge

This researcher has briefly outlined several contributions to the current knowledge generally and to the sustainability of housing industry from an environmental, economic, and professional aspects of adopting 3D printing technology in the Saudi housing sector. these are as follows:

1. This study is the first comprehensive LCA study that was done on several types of construction methods namely conventional villa, precast villa, 3D printing standard villa, and 3D printing innovative villa on a full-scale house from cradle to site.

2. This study is the first economic study that was done on several types of construction methods namely conventional villa, precast villa, 3D printing standard villa, and 3D printing innovative villa on a full-scale house.

3. This study confirmed that even with the positive environmental and economic impacts of 3D printing technology, more future innovation on 3D printing technology can enhance the positive environmental and economic impacts that this technology already has.
4. This study is the first that explored the construction industry perception (architects and civil engineers) on adopting 3D printing technology as a new construction method for houses in Saudi Arabia.

7.5. Recommendations

The study's findings and limitations enabled important recommendations to be provided for future research and to the construction industry, designers, decision-makers, and real estate developers.

- Although 3D printing technology in construction has proven to have lots of advantages in regard to the environment, economy, and society, is still in an early process and needs further examination.
- The system boundary of the LCA study was cradle-to-gate, which was a result of the lack of information on 3D printing technology in construction, so, this research recommends future researchers including himself to continue their research to get to a point where they can conduct a full LCA study with is cradle-to-grave.
- Due to the absence of codes and regulations for 3D printing technology in construction, the design of the elements was done according to the literature and industry practice; so, this research recommends that the design of the 3D printing elements should be modified when there are new codes and regulations for 3D printing technology.
- This research recommends that the LCA research society in Saudi Arabia should collaborate to add the proper specifications for the materials in Saudi Arabia to the LCA software to get the most accurate results when conducting an LCA study.

- The structural and thermal aspects were not in the scope of this study, so, this study recommends a section of the wall to be printed and tested in the future.
- The result of the economic study reveals that 3D printing technology construction methods have a better economic impact when compared to conventional construction methods, but the study was done in Saudi Arabia so this research recommends that other researchers should conduct the same study in another country to see how much the economic impact is.
- This research would like to encourage designers when designing houses to take into account the effect of concrete and steel on greenhouse gas (GHG) emissions.
- The Saudi Building Code National Committee (SBCNC) is the administrative and legal sector that is setting the technical requirements and regulations for buildings in Saudi Arabia. This research recommends that SBCNC should take into consideration adding new codes and regulations for 3D printed houses in Saudi Arabia with the help of experts from the field.
- 3D printing technology has proved that it can achieve more sustainability in construction than conventional construction methods, so, this research recommends the people who take responsibility for the initiatives of houses in Saudi Arabia Vision 2030 to speed up the adoption process for this technology.
- Since professionals (Architects and Civil Engineers) are willing to adopt 3D printing technology in their work, construction companies and architecture firms are encouraged to carry out workshops for their employees in the construction field to learn more about the process of 3D printing technology in the construction sector.
- The findings of this research show that 3D printing technology construction methods have the ability to save cost and time compared to the conventional construction methods, so, this research recommends that real estate developers should consider adopting this technology into their work.

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Appendix A

Appendix A

- **Conventional Villa**

Conventional Villa							
	Material/ Component	**Usage**	**Quantity**		**Density**		**Weight (kg)**
			Amount	**Unit**	**Amount**	**Unit**	
1	Concrete	Ready mix concrete (roof, columns,beams, footings)	**401.68**	**m3**	2,500	**kg/m3**	1,004,200
2	steel bars	footings,cols,beams,slab	**52.72**	**ton**			52,720
3	Concrete masonry units (CMU)	Exterior and interior walls and U.G. masonry	**6,972.25**	**Pcs**			86,455.90
4	Glass	Windows	**0.28**	**m3**	2,500	**kg/m3**	690.00
5	Aluminum	Framing	**64.80**	**l.m**			96.49
6	Wood	Doors	**1.30**	**m3**	770.00	**kg/m3**	1,001.00
7	Ceramic tiles	Room tiles	**270.00**	**m2**	12	**kg/m2**	3,240
8	Ceramic flooring tiles	Bathroom and kitchen floor tiles	**37.00**	**m2**	12	**kg/m2**	444
9	Ceramic walling tiles	Bathroom and kitchen wall tiles	**116.32**	**m2**	12	**kg/m2**	1,395.84
11	Mortar	Exterior and interior walls	**28.47**	**m3**	2,160	**kg/m3**	61,495.20
12	Gypsum	ceiling	**3.68**	**m3**	12.30	**kg/m2**	45.26
13	Polystyrene (EPS)	Thermal insulation for roof slab	**15.50**	**m3**	32	**kg/m3**	496
15	Polyethylene	Vapor barrier (foundation)	**0.16**	**m3**	955	**kg/m3**	152.80
16	Bitumen Membrane	On top of the roof	**329.69**	**m2**	4.70	**kg/m2**	1,549.54
17	Bitumen Paint	Water proofing (foundation)	**377.00**	**m2**	4.70	**kg/m2**	1,771.90

18	Paint						
19	White Paint	Interior	**774.05**	**m2**			58.64
20	Textured Paint	Exterior	**464.30**	**m2**			35.17
21	Polystyrene (EPS) inside masonry	Thermal insulation for outer walls	**17.49**	**m3**	32	**kg/m3**	559.68
22	Polyvinyle chloride (PVC)-plumbing	Sewer line	**280**	**l.m**			336
		water line	**780**	**l.m**			172
23	Wood	Formwork	**5.74**	**m3**	800	**kg/m3**	4,592

- **Concrete Truck & Concrete Pump Electricity Consumption for Conventional Villa**

Concrete Truck Mixer			
ENERGY CALC.			
Concrete volume	401.68	m3	
motion speed	4	m3/min	
total time	100.42	min	
time as hour	1.67	hr	
power as 100%	17.50	kw	
power as 50%	8.75	kw	
Power consump.	**14.64**	**kwh**	50%
	29.29	**kwh**	100%
Concrete volume	401.68	m3	
motion speed	0.5	m3/min	
total time	803.36	min	
time as hour	13.39	hr	
power as 100%	260.00	kw	
power as 50%	130.00	kw	
Power consump.	**1740.61**	**kwh**	50%
	3481.23	**kwh**	100%

- **Precast Villa**

Precast Villa							
	Material/ Component	**Usage**	**Quantity**		**Density**		**Weight (kg)**
			Amount	**Unit**	**Amount**	**Unit**	
1	Concrete	Ready mix concrete (footings)	**240.94**	**m3**	2,500	**kg/m3**	602,350
2	steel bars	footings	**31.62**	**ton**			31,623.38
3	Precast walls						
4	concrete	Interior and Exterior walls	**127.10**	**m3**	2,500	**kg/m3**	317,750
5	steel bars	Interior and Exterior walls	**11.04**	**ton**			11044.99
6	Glass	Windows	**0.28**	**m3**	2,500	**kg/m3**	700.00
7	Aluminum	Framing	**64.80**	**l.m**			96.49
8	Wood	Doors	**1.30**	**m3**	770.00	**kg/m3**	1,001.00
9	Ceramic tiles	Room tiles	**270.00**	**m2**	12	**kg/m2**	3,240
10	Ceramic flooring tiles	Bathroom and kitchen floor tiles	**37.00**	**m2**	12	**kg/m2**	444
11	Ceramic wall tiles	Bathroom and kitchen wall tiles	**116.32**	**m2**	12	**kg/m2**	1,395.84
12	Gypsum	ceiling	**3.68**	**m3**	12.30	**kg/m2**	45.26
13	Polystyrene (EPS)	Thermal insulation for roof slab	**15.50**	**m3**	32	**kg/m3**	496
14	Polyethylene	Vapor barrier (foundation)	**0.16**	**m3**	955	**kg/m3**	152.80
15	Bitumen Membrane	On top of the roof	**329.69**	**m2**	4.70	**kg/m2**	1,549.54
16	Bitumen Paint	Water proofing (foundation)	**377.00**	**m2**	4.70	**kg/m2**	1,771.90
17	Paint						
18	White Paint	Interior	**774.05**	**m2**			58.64
17	Textured Paint	Exterior	**464.30**	**m2**			35.17
18	Polystyrene (EPS) inside masonry	Thermal insulation for outer walls	**7.33**	**m3**	32	**kg/m3**	234.56
19	Polyvinyle chloride (PVC)-plumbing	Sewer line	**280**	**l.m**			336
20		water line	**780**	**l.m**			172
21	Wood	Formwork (footing)	**0.81**	**m3**	800	**kg/m3**	651.20

Precast Villa							
	Material/ Component	Usage	Quantity		Density		Weight (kg)
			Amount	Unit	Amount	Unit	
22	Concrete	Hollow core slab	**49.04**	**m3**	2,500	**kg/m3**	122,600
	Wire strands		**0.77**	**ton**			773.28
	Steel bars	Steel net above Hollow core slab	**2.67**	**ton**			2665.05
	Concrete	concrete above Hollow core slab	**21.73**	**m3**	2,500	**kg/m3**	54,320
23	Steel sheet	Formwork in factory for Interior and Exterior walls	**51.86**	**ton**			51862

- **Concrete Truck & Concrete Pump Electricity Consumption for Precast Villa**

Concrete Truck Mixer			
ENERGY CALC.			
Concrete volume	438.81	m3	
motion speed	4	m3/min	
total time	**109.70**	min	
time as hour	1.83	hr	
power as 100%	17.50	kw	
power as 50%	8.75	kw	
Power consump.	**16.00**	**kwh**	50%
	32.00	**kwh**	100%

Concrete Truck Pump			
ENERGY CALC.			
Concrete volume	438.81	m3	
motion speed	0.5	m3/min	

total time	**877.62**	min	
time as hour	14.63	hr	
power as 100%	260.00	kw	
power as 50%	130.00	kw	
Power consump.	**1901.51**	**kwh**	50%
	3803.02	**kwh**	100%

- **Electric consumption for Hollowcore Slab for Precast Villa**

Concrete Hollow Core Slab Making Machine			
ENERGY CALC.			
Casting length	267	m	
motion speed	1.85	m/min	
total time	**144.32**	min	
time as hour	2.41	hr	
power as 100%	45.00	kw	
power as 50%	22.50	kw	
Power consump.	**54.12**	**kwh**	50%
	108.24	**kwh**	100%
Wire Strands Machine			
ENERGY CALC.			
Casting length	267	m	
motion speed	36	m/min	
total time	**7.42**	min	
time as hour	0.12	hr	
power as 100%	13.00	kw	
power as 50%	6.50	kw	
Power consump.	**0.80**	**kwh**	50%
	1.61	**kwh**	100%

- **Standard 3D Printed Villa**

Standard 3D Printed Villa							
	Material/ Component	**Usage**	**Quantity**		**Density**		**Weight (kg)**
			Amount	**Unit**	**Amount**	**Unit**	
1	Concrete	Ready mix concrete (footings)	**154.50**	**m3**	2,500	**kg/m3**	386,253
2	Steel bars	(footings)	**19.31**	**ton**		**ton**	19,312.65
3	Glass	Windows	**0.28**	**m3**	2,500	**kg/m3**	700.00
4	Aluminum	Framing	**64.80**	**l.m**			96.49
5	Wood	Doors	**1.30**	**m3**	770.00	**kg/m3**	1,001.00
6	Ceramic tiles	Room tiles	**270.42**	**m2**	12	**kg/m2**	3,245.05
7	Ceramic flooring tiles	Bathroom and kitchen floor tiles	**36.13**	**m2**	12	**kg/m2**	433.62
8	Ceramic wall tiles	Bathroom and kitchen wall tiles	**116.13**	**m2**	12	**kg/m2**	1,393.54
9	Gypsum	Ceiling	**3.68**	**m3**	12.30	**kg/m3**	45.25
10	Polystyrene (EPS)	Thermal insulation for roof slab	**14.68**	**m3**	32	**kg/m3**	469.60
11	Polyethylene	Vapor barrier (foundation)	**0.17**	**m3**	955	**kg/m3**	159.68
12	Bitumen Membrane	On top of the roof	**329.12**	**m2**	4.70	**kg/m2**	1,546.88
13	Bitumen Paint	Water proofing (foundation)	**359.26**	**m2**	4.70	**kg/m2**	1,688.52
15	Paint						
16	White Paint	Interior	**768.16**	**m2**			58.19
17	Textured Paint	Exterior	**465.22**	**m2**			35.24
18	Polyvinyle chloride (PVC)-plumbing	Sewer line	**280**	**l.m**			336
19		Water line	**780**	**l.m**			172
20	Wood	Formwork for footings	**0.62**	**m3**	800	**kg/m3**	498
21	Concrete	Hollow core slab	**51.4**	**m3**	2,500	**kg/m3**	128,500

Standard 3D Printed Villa							
	Wire strands		**0.79**	**ton**			792.89
	Steel bars	Steel net above Hollow core slab	**2.87**	**ton**			2872.12
	Concrete	concrete above Hollow core slab	**23.41**	**m3**	2,500	**kg/m3**	58,520

- **Concrete Truck & Concrete Pump Electricity Consumption for Standard 3D Printed Villa**

Concrete Truck Mixer			
ENERGY CALC.			
Concrete volume	229.3	m3	
motion speed	4	m3/min	
total time	**57.33**	min	
time as hour	0.96	hr	
power as 100%	17.50	kw	
power as 50%	8.75	kw	
Power consump.	**8.36**	**kwh**	50%
	16.72	**kwh**	100%

Concrete Truck Pump			
ENERGY CALC.			
Concrete volume	229.3	m3	
motion speed	0.5	m3/min	
total time	**458.60**	min	
time as hour	7.64	hr	
power as 100%	260.00	kw	
power as 50%	130.00	kw	
Power consump.	**993.63**	**kwh**	50%
	1987.27	**kwh**	100%

- **Electric consumption for Hollowcore Slab for Standard 3D Printed Villa**

Concrete Hollow Core Slab Making Machine			
ENERGY CALC.			
Casting length	251.5	m	
motion speed	1.85	m/min	
total time	**135.95**	min	
time as hour	2.27	hr	
power as 100%	45.00	kw	
power as 50%	22.50	kw	
Power consump.	**50.98**	**kwh**	50%
	101.96	**kwh**	100%
Wire Strands Machine			
ENERGY CALC.			
Casting length	251.5	m	
motion speed	36	m/min	
total time	**6.99**	min	
time as hour	0.12	hr	
power as 100%	13.00	kw	
power as 50%	6.50	kw	
Power consump.	**0.76**	**kwh**	50%
	1.51	**kwh**	100%

- **Standard 3D Printed Concrete Volume**

Volume	54.14 m3
Density	2250
Total	121830.75

3DP Concrete Mix	**Le et al. (2012)**	**Percentage**
Cement	30457.69	25.00%
Fly-ash	8649.98	7.10%
Silicafume	4385.91	3.60%
Sand/ aggregates	65179.45	53.50%
Water	12183.08	10.00%
Polycarboxylate ether superplasticiser (SP)	852.82	0.70%
Fibre	60.92	0.05%
Total	**121830.75**	

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- **Electric consumption for 3D Printing Robot (KR 120 R3900 ultra K)**

ENERGY CALC.			
All print length	149110.022	m	
motion speed	0.25	m/sec	
total time	**9940.67**	min	
time as hour	165.68	hr	
power as 100%	15.80	kw	
power as 50%	7.90	kw	
Power consump.	**1308.9**	**kwh**	50%
	2617.7	**kwh**	100%

- **Electric Consumption for 3D Printing Concrete Mixer and Pump (M-tec Duomix Connect)**

ENERGY CALC.			
Volume of concrete	54.147	m3	
m3 to L	54147	L	
pump rate	22	L/m	
total time	2461.227273	min	
time as hour	41.02045455	hr	
power as 100%	10.35	kw	
power as 50%	5.175	kw	
Power consump.	**212.28**	**kwh**	50%
	424.56	**kwh**	100%

- **Electric Consumption for 3D Printing Gantry (Cobod 2)**

ENERGY CALC FOR THE BUILDING.			
All print length	149110.022	m	
motion speed	0.25	m/sec	
total time	**9940.67**	min	
time as hour	165.68	hr	
power as 100%	15.66	kw	
power as 50%	7.83	kw	
Power consump.	**1297.34**	**kwh**	50%
	2594.68	**kwh**	100%

- **Innovative 3D Printed Villa**

Innovative 3D Printed Villa							
	Material/Component	**Usage**	**Quantity**		**Density**		**Weight (kg)**
			Amount	**Unit**	**Amount**	**Unit**	
	Concrete	Ready mix concrete (footings)	**143.35**	**m3**	2,500	**kg/m3**	358,375
1	Steel bars	(footings, steel ties)	**19.51**	**ton**		**ton**	19,510
2	Glass	Windows	**0.4512**	**m3**	2,500	**kg/m3**	1,128.00
3	Aluminum	Framing	**98.2**	**l.m**			146.22
4	Wood	Doors	**1.6515**	**m3**	770.00	**kg/m3**	1,271.66
5	Ceramic tiles	Room tiles	**235.05**	**m2**	12	**kg/m2**	2,820.64
6	Ceramic flooring tiles	Bathroom and kitchen tiles	**46.79**	**m2**	12	**kg/m2**	561.46
	Ceramic wall tiles	Bathroom and kitchen wall tiles	**209.46**	**m2**	12	**kg/m2**	2,513.55
7	Gypsum	Ceiling	**3.07**	**m3**	12.30	**kg/m3**	37.76

9	Polystyrene (EPS)	Thermal insulation for roof slab	**15.03**	**m3**	32	**kg/m3**	481.04
10	Polyethylene	Vapor barrier (foundation)	**0.15**	**m3**	955	**kg/m3**	147.91
11	Bitumen Membrane	On top of the roof	**286.58**	**m2**	4.70	**kg/m2**	1,346.93
12	Bitumen Paint	Water proofing (foundation)	**331.14**	**m2**	4.70	**kg/m2**	1,556.34
13	Paint						
14	White Paint	Interior	**729.97**	**m2**			55
	Textured Paint	Exterior	**381.58**	**m2**			28.91
15	Polyvinyle chloride (PVC)-plumbing	Sewer line	**280**	**l.m**			336
		Water line	**780**	**l.m**			172
16	Wood	Formwork for footings	**0.54**	**m3**	800	**kg/m3**	428.04
17	Concrete	Hollow core slab	**47.87**	**m3**	2,500	**kg/m3**	119,675
	Wire strands		**0.76**	**ton**			759.11
	Steel bars	Steel net above Hollow core slab	**2.63**	**ton**			2632.11
	Concrete	concrete above Hollow core slab	**21.1**	**m3**	2,500	**kg/m3**	52,750

- **Concrete Truck & Concrete Pump Electricity Consumption for Innovative 3D Printed Villa**

Concrete Truck Mixer			
ENERGY CALC.			
Concrete volume	164.45	m3	
motion speed	4	m3/min	
total time	**41.11**	min	
time as hour	0.69	hr	
power as 100%	17.50	kw	
power as 50%	8.75	kw	
	11.99	**kwh**	100%

Concrete Truck Pump			
ENERGY CALC.			
Concrete volume	164.45	m3	
motion speed	0.5	m3/min	
total time	**328.90**	min	
time as hour	5.48	hr	
power as 100%	260.00	kw	
power as 50%	130.00	kw	
Power consump.	**712.62**	**kwh**	50%
	1425.23	**kwh**	100%

- **Electricity Consumption for Hollowcore Slab for Innovative 3D Printed Villa**

Concrete Hollow Core Slab Making Machine			
ENERGY CALC.			
Casting length	256.12	m	
motion speed	1.85	m/min	
total time	**138.44**	min	
time as hour	2.31	hr	
power as 100%	45.00	kw	
power as 50%	22.50	kw	
	103.83	**kwh**	100%
Wire Strands Machine			
ENERGY CALC.			
Casting length	256.12	m	
motion speed	36	m/min	
total time	**7.11**	min	
time as hour	0.12	hr	
power as 100%	13.00	kw	
power as 50%	6.50	kw	

Concrete Hollow Core Slab Making Machine			
ENERGY CALC.			
Power consump.	**0.77**	**kwh**	50%
	1.54	**kwh**	100%

- **Innovative 3D Printed Villa Concrete Volume**

Volume	41.98 m3
Density	2250
Total	94455

3DP Concrete Mix	Le et al. (2012)	Percentage
Cement	23613.75	25.00%
Fly-ash	6706.31	7.10%

Silicafume	3400.38	3.60%
Sand/ aggregates	50533.43	53.50%
Water	9445.5	10.00%
Polycarboxylate ether superplasticiser (SP)	661.19	0.70%
Fibre	47.23	0.05%
Total	94455	

- **Electric Consumption for 3D Printing Gantry (Cobod 2)**

ENERGY CALC.			
All print length	124,574.41	m	
motion speed	0.25	m/sec	
total time	**8304.96**	min	
time as hour	138.42	hr	
power as 100%	15.66	kw	
power as 50%	7.83	kw	
Power consump.	**1083.87**	**kwh**	50%
	2167.73	**kwh**	100%

- **Electric Consumption for 3D Printing Concrete Mixer and Pump (M-tec Duomix Connect)**

Electric Consumption for 3D Printing Concrete Mixer and Pump (M-tec Duomix Connect)			
ENERGY CALC.			
Volume of concrete	41.98	m3	
m3 to L	41980	L	
pump rate	22	L/m	
total time	1908.181818	min	
time as hour	31.8030303	hr	
power as 100%	10.35	kw	
power as 50%	5.175	kw	
Power consump.	**164.581**	**kwh**	50%
	329.161	**kwh**	100%

- **Electric consumption for 3D Printing Robot (KR 120 R3900 ultra K)**

ENERGY CALC.			
All print length	124,574.41	m	
motion speed	0.25	m/sec	
total time	**8304.96**	min	
time as hour	138.42	hr	
power as 100%	15.80	kw	
power as 50%	7.90	kw	
Power consump.	**1093.49**	**kwh**	50%
	2186.97	**kwh**	100%

- **Transportation Calculations**

Conventional Villa (Transportation)							
	Material/ Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation (km)**	**Kgkm**	**Tonkm**
1	Concrete	Ready mix concrete (roof, columns,beams, footings)	1004200	1004.2	26	26109200	26109.2
2	steel bars	footings,cols,beams,slab	52720	52.72	10	527200	527.2
3	Concrete masonry units (CMU)	Exterior and interior walls and U.G. masonry	86455.9	86.4559	26	2247853.4	2247.8534
4	Glass	Windows	690	0.69	10	6900	6.9

Conventional Villa (Transportation)							
	Material/ Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation (km)**	**Kgkm**	**Tonkm**
5	Aluminum	Framing	96.49	0.09649	1 0	964.9	0.9649
6	Wood	Doors	1001	1.001	10	10010	10.01
7	Ceramic tiles	Room tiles	3240	3.24	10	32400	32.4
8	Ceramic flooring tiles	Bathroom and kitchen floor tiles	444	0.444	10	4440	4.44
9	Ceramic walling tiles	Bathroom and kitchen wall tiles	1395.84	1.39584	10	13958.4	13.9584
11	Mortar	Exterior and interior walls	61495.2	61.4952	10	614952	614.952
12	Gypsum	ceiling	45.264	0.045264	10	452.64	0.45264
13	Polystyrene (EPS)	Thermal insulation for roof slab	496	0.496	10	4960	4.96
15	Polyethylene	Vapor barrier (foundation)	152.8	0.1528	10	1528	1.528
16	Bitumen Membrane	On top of the roof	1549.543	1.549543	10	15495.43	15.49543

Conventional Villa (Transportation)							
	Material/ Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation (km)**	**Kgkm**	**Tonkm**
17	Bitumen Paint	Water proofing (foundation)	1771.9	1.7719	10	17719	17.719
18	Paint						
19	White Paint	Interior	58.64	0.05864	10	586.4	0.5864
20	Textured Paint	Exterior	35.17	0.03517	10	351.7	0.3517
21	Polystyrene (EPS) inside masonry	Thermal insulation for outer walls	559.68	0.55968	10	5596.8	5.5968
22	Polyvinyle chloride (PVC)-plumbing	Sewer line	336	0.336	10	3360	3.36
		water line	171.6	0.1716	10	1716	1.716
23	Wood	Formwork	4592	4.592	10	45920	45.92
						Total	29665.56

Precast Villa (Transportation)							
	Material/Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation (km)**	**Kgkm**	**Tonkm**
1	Concrete	Ready mix concrete (footings)	602,350.00	602.35	26	15,661,100.00	15,661
2	steel bars	footings	31,623.38	31.623375	10.00	316,233.75	316.23
3	Precast walls						
	concrete	Interior and Exterior walls	317,750.00	317.75	10	3,177,500.00	3,178
	steel bars	Interior and Exterior walls	11044.99	11.04499	10	110449.9	110.4499
4	Glass	Windows	700.00	0.7	10	7,000.00	7.00
5	Aluminum	Framing	96.49	0.09649	10.00	964.90	0.96
6	Wood	Doors	1,001.00	1.001	10.00	10,010.00	10.01
7	Ceramic tiles	Room tiles	3,240.00	3.24	10	32,400.00	32
8	Ceramic flooring tiles	Bathroom and kitchen floor tiles	444.00	0.444	10	4,440.00	4
9	Ceramic wall tiles	Bathroom and kitchen wall tiles	1,395.84	1.39584	10	13,958.40	13.96
10	Gypsum	ceiling	45.26	0.045264	10.00	452.64	0.45
11	Polystyrene (EPS)	Thermal insulation for roof slab	496.00	0.496	10	4,960.00	5
12	Polyethylene	Vapor barrier (foundation)	152.80	0.1528	10	1,528.00	1.53
13	Bitumen Membrane	On top of the roof	1,549.54	1.54954065	10.00	15,495.41	15.50

Precast Villa (Transportation)							
	Material/Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation (km)**	**Kgkm**	**Tonkm**
14	Bitumen Paint	Water proofing (foundation)	1,771.90	1.7719	10.00	17,719.00	17.72
15	Paint						
16	White Paint	Interior	58.64	0.05864	10.00	586.40	0.59
17	Textured Paint	Exterior	35.17	0.03517	10.00	351.70	0.35
18	Polystyrene (EPS) inside masonry	Thermal insulation for outer walls	234.56	0.23456	10	2,345.60	2.35
19	Polyvinyle chloride (PVC)-plumbing	Sewer line	336	0.336	10.00	3,360.00	3
20		water line	172	0.1716	10.00	1,716.00	2
21	Wood	Formwork (footing)	651.20	0.6512	10	6,512.00	6.51
22	Concrete	Hollow core slab	122600	122.6	26	3,187,600.00	3,188
	Wire strands		773.28	0.77328	26	20105.28	20.10528
	Steel bars	Steel net above Hollow core slab	2665.05	2.66505	26	69291.3	69.2913
	Concrete	concrete above Hollow core slab	54320.00	54.32	26	1,412,320.00	1,412
23	Steel sheet	Formwork in factory for Interior and Exterior walls	51862.00	51.862			
						Total	32055.67

Standard 3D Printed Villa (Transportation)							
	Material/Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation**	**Kgkm**	**Tonkm**
1	Concrete	Ready mix concrete (footings)	386253.00	386.253	26	10,042,578.00	10,043
2	Steel bars	(footings)	19312.65	19.31265	10.00	193,126.50	193.13
3	Glass	Windows	700.00	0.7	10	7,000.00	7.00
4	Aluminum	Framing	96.49	0.09649	10.00	964.90	0.96
5	Wood	Doors	1,001.00	1.001	10.00	10,010.00	10.01
6	Ceramic tiles	Room tiles	3245.05	3.24505314	10	32,450.53	32.45
7	Ceramic flooring tiles	Bathroom and kitchen floor tiles	433.62	0.43361766	10	4,336.18	4.34
8	Ceramic wall tiles	Bathroom and kitchen wall tiles	1,393.54	1.393536	10	13,935.36	13.94
9	Gypsum	Ceiling	45.25	0.045247651	10.00	452.48	0.45
10	Polystyrene (EPS)	Thermal insulation for roof slab	469.60	0.4696	10	4,696.00	4.70
11	Polyethylene	Vapor barrier (foundation)	159.68	0.159676	10	1,596.76	1.60
12	Bitumen Membrane	On top of the roof	1546.88	1.54687575	10.00	15,468.76	15.47
13	Bitumen Paint	Water proofing (foundation)	1688.522	1.688522	10.00	16,885.22	16.89

Standard 3D Printed Villa (Transportation)							
	Material/Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation**	**Kgkm**	**Tonkm**
15	Paint						
16	White Paint	Interior	58.19	0.05819	10.00	581.90	0.58
17	Textured Paint	Exterior	35.24	0.03524	10.00	352.40	0.35
18	Polyvinyle chloride (PVC)-plumbing	Sewer line	336	0.336	10.00	3,360.00	3
19		Water line	172	0.1716	10.00	1,716.00	2
20	Wood	Formwork for footings	498.00	0.50	10	4,980.00	5
21	Concrete	Hollow core slab	128500	128.5	26	3,341,000.00	3,341
	Wire strands		792.89	0.79289	26	20615.14	20.61514
	Steel bars	Steel net above Hollow core slab	2872.12	2.872121	26	74675.146	74.68
	Concrete	concrete above Hollow core slab	58520.00	58.52	26	1,521,520.00	1,522
					Total		20271.83

Transportation for 3D Concrete Mix for Standard 3D Printed Villa		
Weight	Unit	Tonkm
121.83	ton	3167.60

Transportation for 3D Printing Robot (KR 120 R3900 ultra K) for Standard 3D Printed Villa			
Weight	**Unit**	**Tonkm**	
1.221	**ton**	**31.75**	**KR 120 R3900 ultra K**
0.26	**ton**	**6.76**	**M-tec Duomix Connect**

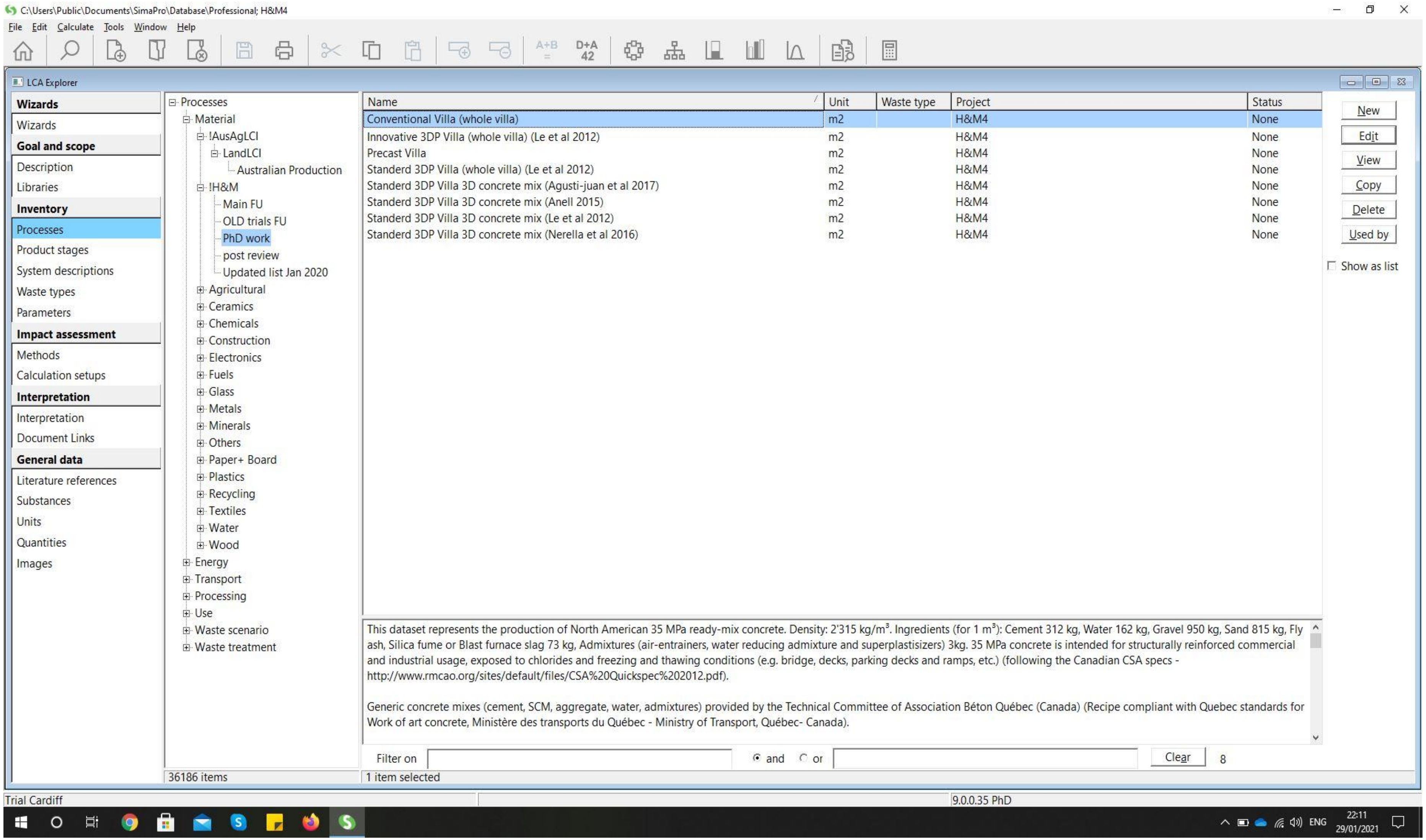
Innovative 3D Printed Villa (Transportation)							
	Material/ Component	Usage	Weight (kg)	Weight (ton)	Transportation	Kgkm	Tonkm
	Concrete	Ready mix concrete (footings)	358375	358.375	26	9,317,750.00	9,318
1	Steel bars	(footings, steel ties)	19510	19.51	10.00	195,100.00	195
2	Glass	Windows	1128	1.128	10	11,280.00	11.28
3	Aluminum	Framing	146.2198	0.1462198	10	1,462.20	1.46
4	Wood	Doors	1271.655	1.271655	10.00	12,716.55	12.72
5	Ceramic tiles	Room tiles	2820.64	2.820636	10	28,206.36	28.21
6	Ceramic flooring tiles	Bathroom and kitchen tiles	561.46	0.561456	10	5,614.56	5.61
	Ceramic wall tiles	Bathroom and kitchen wall tiles	2513.55	2.5135488	10	25,135.49	25.14
7	Gypsum	Ceiling	37.761	0.037761	10.00	377.61	0.38
9	Polystyrene (EPS)	Thermal insulation for roof slab	481.04	0.48104	10	4,810.40	4.81
10	Polyethylene	Vapor barrier (foundation)	147.91	0.1479104	10	1,479.10	1.48
11	Bitumen Membrane	On top of the roof	1346.926	1.346926	10.00	13,469.26	13.47
12	Bitumen Paint	Water proofing (foundation)	1556.34	1.5563392	10.00	15,563.39	15.56
13	Paint						
14	White Paint	Interior	55.30	0.0553	10.00	553.00	1
	Textured Paint	Exterior	28.91	0.02891	10.00	289.10	0.29
15	Polyvinyle chloride (PVC)-plumbing	Sewer line	336	0.336	10.00	3,360.00	3
		Water line	172	0.1716	10.00	1,716.00	2
16	Wood	Formwork for footings	428.04	0.43	10	4,280.40	4.28

Innovative 3D Printed Villa (Transportation)								
	Material/ Component	**Usage**	**Weight (kg)**	**Weight (ton)**	**Transportation**	**Kgkm**	**Tonkm**
	Concrete	Ready mix concrete (footings)	358375	358.375	26	9,317,750.00	9,318
	Concrete	Hollow core slab	119675	119.675	26	3,111,550.00	3,112
	Wire strands		759.11	0.75911	26	19736.86	19.73686
	Steel bars	Steel net above Hollow core slab	2632.11	2.632114	26	68434.964	68.43
	Concrete	concrete above Hollow core slab	52750	52.75	26	1,371,500.00	1,372
					Total		18785.61

Transportation for 3D Concrete Mix for Innovative 3D Printed Villa		
Weight	Unit	Tonkm
94.46	ton	2455.83

Transportation for 3D Printing Gantry for Innovative 3D Printed Villa			
Weight	**Unit**	**Tonkm**	
5.023	**ton**	**130.598**	**Cobod 2**
0.26	**ton**	**6.76**	**M-tec Duomix Connect**

- **Screenshot of SimaPro**



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File Edit Calculate Tools Window Help

Documentation | **Input/output** | Parameters | System description

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Conventional Villa (whole villa)	310.16	m2	Area	100 %		!H&M\PhD work	
Add							

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	518.49	kg	Undefined		Interior and Exterior
Bitumen adhesive compound, hot {RoW}| production | APOS, U	1771.90	kg	Undefined		bitumen foundation
H Bitumen seal {RoW}| production | APOS, U	1549.54	kg	Undefined		bitumen paint for roof
H Ceramic tile {RoW}| production | APOS, U	5079.84	kg	Undefined		Room tiles+bathroom and kitchen tiles for flooring and walls
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
H Gypsum fibreboard {RoW}| production | APOS, U	45.26	kg	Undefined		
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H&M Cement mortar {RoW}| production | APOS, U	61495.20	kg	Undefined		
H&M Concrete block {RoW}| production | APOS, U	6972.25	kg	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	5.74	m3	Undefined		formwork
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	29670.90	tkm	Undefined		concrete car empty
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	401.68	m3	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	152.80	kg	Undefined		foundation
Polystyrene foam slab {RoW}| production | APOS, U	1005.68	kg	Undefined		for roof and walls
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	2226	kg	Undefined		water and swear pipes
Reinforcing steel {RoW}| production | APOS, U	52.72	ton	Undefined		
Add					

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| production mix | APOS, U	1755.26	kWh	Undefined				Concrete trcuk and Concrete pump
Add							

Trial Cardiff 9.0.0.35 PhD

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File Edit Calculate Tools Window Help

Documentation | **Input/output** | Parameters | System description

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Precast Villa	310.16	m2	Area	100 %		!H&M\PhD work	
Add							

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	518.49	kg	Undefined		Interior and Exterior
Bitumen adhesive compound, hot {RoW}| production | APOS, U	1771.90	kg	Undefined		bitumen foundation
H Bitumen seal {RoW}| production | APOS, U	1549.54	kg	Undefined		bitumen paint for roof
H Ceramic tile {RoW}| production | APOS, U	5079.84	kg	Undefined		Room tiles+bathroom and kitchen tiles for flooring and walls
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
H Gypsum fibreboard {RoW}| production | APOS, U	45.26	kg	Undefined		
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	0.81	m3	Undefined		formwork
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	32060.90	tkm	Undefined		
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	438.81	m3	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	152.80	kg	Undefined		foundation
Polystyrene foam slab {RoW}| production | APOS, U	730.56	kg	Undefined		for roof and walls
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	2226	kg	Undefined		water and swear pipes
Reinforcing steel {RoW}| production | APOS, U	46.11	ton	Undefined		
Sheet rolling, steel {RoW}| processing | APOS, U	51.86	ton	Undefined		
Add					

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| production mix | APOS, U	1972.43	kWh	Undefined				Concrete trcuk and Concrete pump
Add							

Outputs

Trial Cardiff | 9.0.0.35 PhD

ENG 22:12 29/01/2021

C:\Users\Public\Documents\SimaPro\Database\Professional; H&M4 - [Edit material process 'Standerd 3DP Villa (whole villa) (Le et al 2012)']

File Edit Calculate Tools Window Help

Documentation | **Input/output** | Parameters | System description

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Standerd 3DP Villa (whole villa) (Le et al 2012)	326.06	m2	Area	100 %		!H&M\PhD work	The functional unit here is 1x1x0.4 m load bearing external wall-unfinished ------ 50 MPa concrete is intended for structurally reinforced specialty usage, exposed to chlorides and other severe environments, with or without freezing and thawing conditions, and with high durability performances expectations (e.g. work of art etc.) (following the Canadian CSA specs -

Add

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs

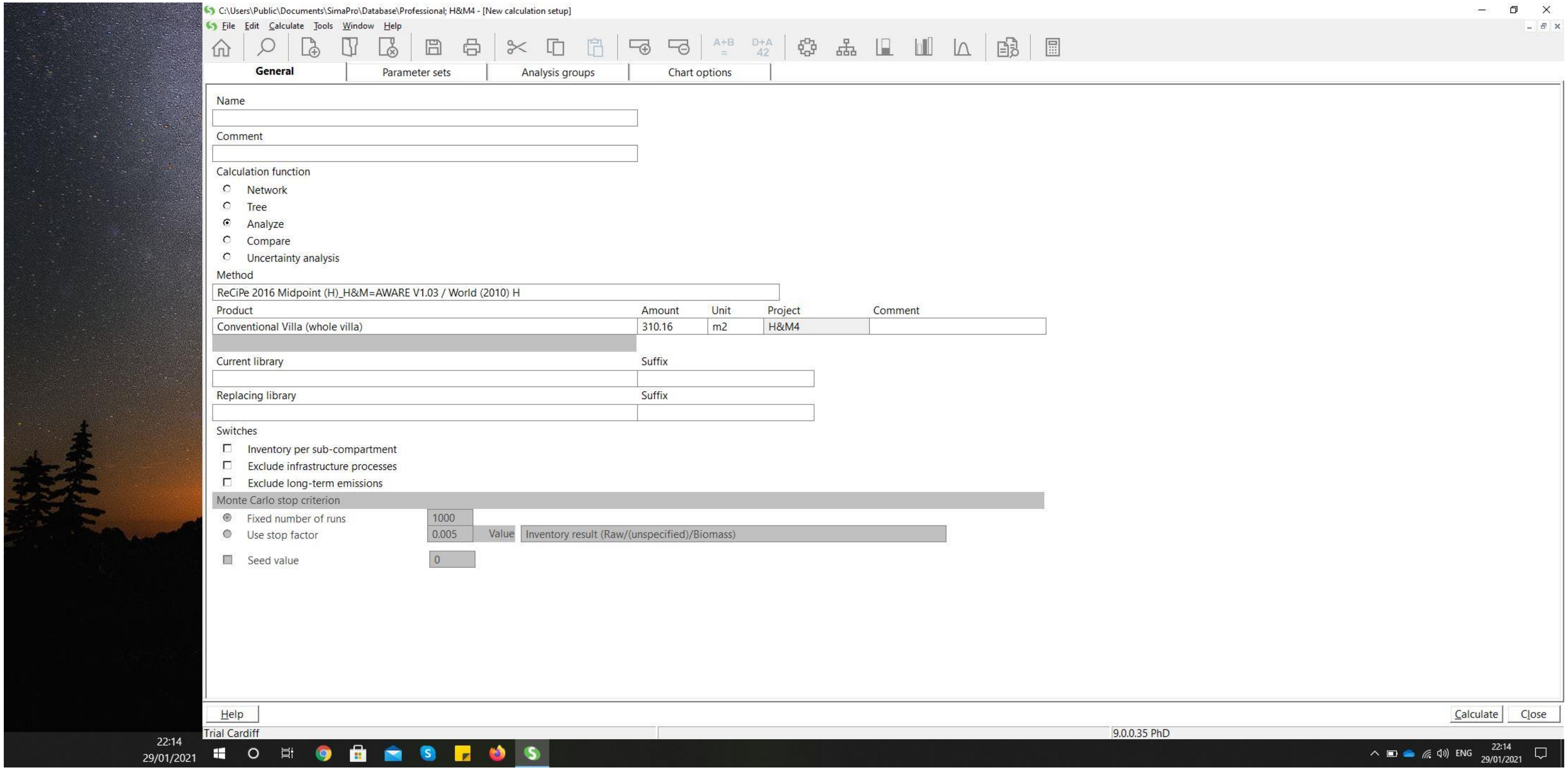
Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

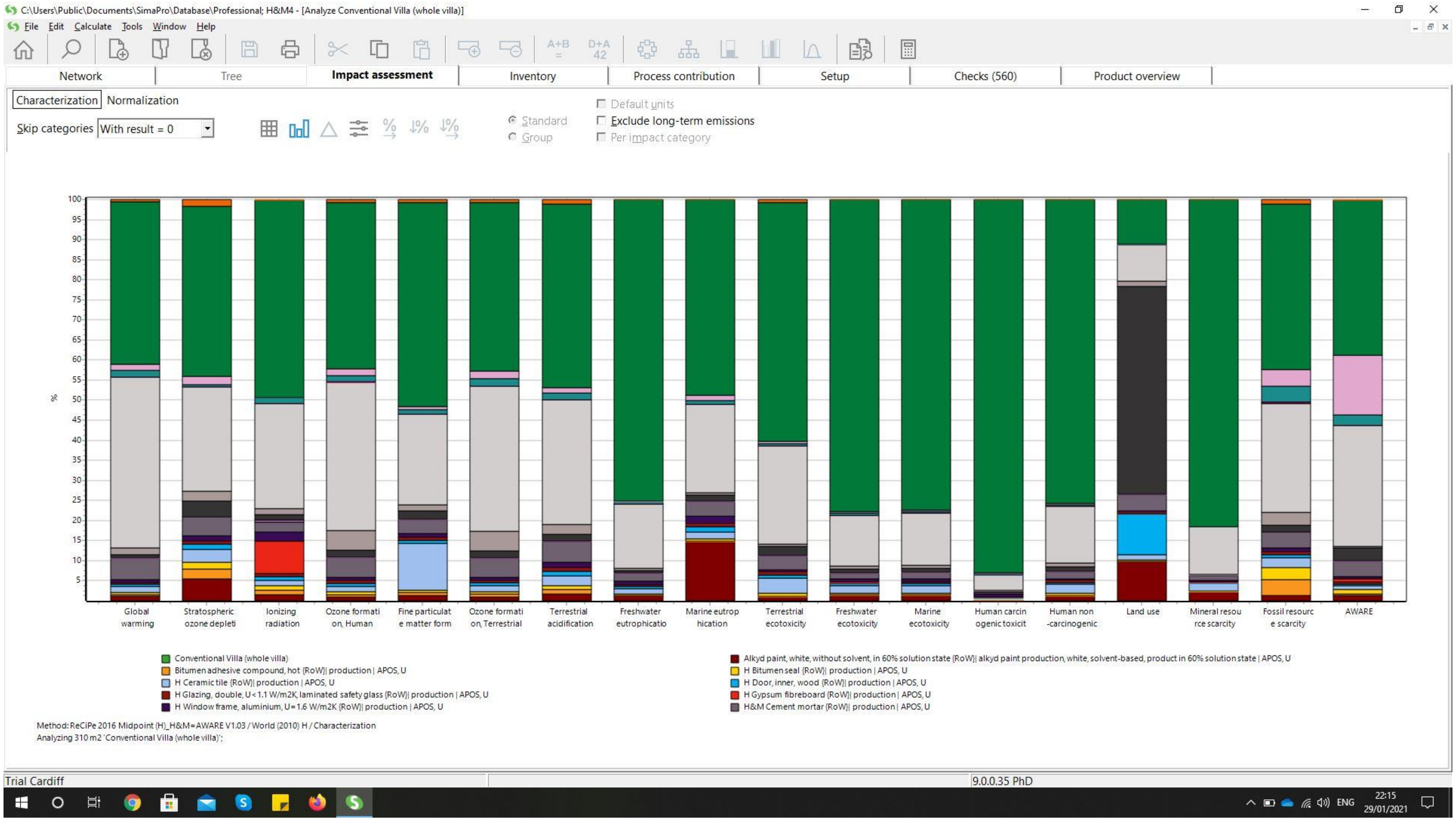
Add

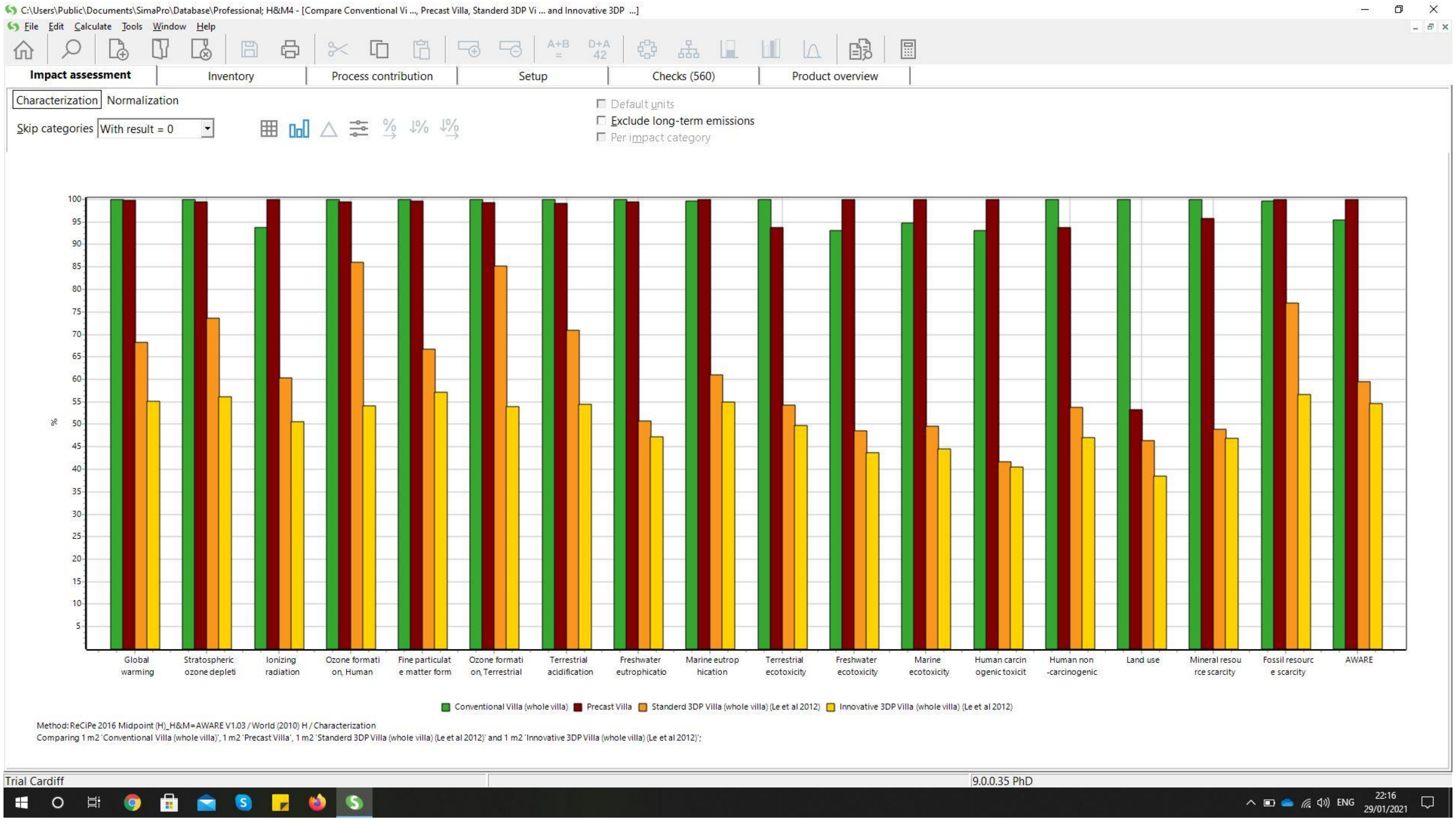
Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
H&M Cement, pozzolana and fly ash 23%, non-US {RoW}| production | APOS, U	39107.67	kg	Undefined		(1,1,4,1,1,na) EcoSpold01Location=CH Including waste concrete. See Exchange Properties
Tap water {RoW}| tap water production, artificial recharged wells | APOS, U	12183.08	kg	Undefined		(1,1,4,1,1,na) EcoSpold01Location=CH Water use in ready-mix plant, assumed to be sourced from municipal water system. See Exchange properties comment for Sources.
Silica fume, densified {GLO}| silica fume, densified, Recycled Content cut-off | Cut-off, U	4385.91	kg	Undefined		
Polycarboxylates, 40% active substance {RoW}| production | APOS, U	852.82	kg	Undefined		
Fibre cement corrugated slab {RoW}| production | APOS, U	60.92	kg	Undefined		
H&M Sand {RoW}| gravel and quarry operation | APOS, U	65179.45	kg	Undefined		
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	38.506	tkm	Undefined		Transportation for KUKA KR robot
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
Reinforcing steel {RoW}| production | APOS, U	22.98	ton	Undefined		
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	229.31	m3	Undefined		62 is for the roof
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
H Ceramic tile {RoW}| production | APOS, U	5072.21	kg	Undefined		room, kichen, and bathroom floors and walls
H Gypsum fibreboard {RoW}| production | APOS, U	45.25	kg	Undefined		

Trial Cardiff 9.0.0.35 PhD

ENG 22:13 29/01/2021


C:\Users\Public\Documents\SimaPro\Database\Professional; H&M4 - [New calculation setup]
File Edit Calculate Tools Window Help
General
Parameter sets
Analysis groups
Chart options
Name
Comment
Calculation function
Network
Tree
Analyze
Compare
Uncertainty analysis
Method
ReCiPe 2016 Midpoint (H)_H&M=AWARE V1.03 / World (2010) H
Product
Amount
Unit
Project
Comment
Conventional Villa (whole villa)
310.16
m2
H&M4
Current library
Suffix
Replacing library
Suffix
Switches
Inventory per sub-compartment
Exclude infrastructure processes
Exclude long-term emissions
Monte Carlo stop criterion
Fixed number of runs
1000
Use stop factor
0.005
Value
Inventory result (Raw/(unspecified)/Biomass)
Seed value
0
Help
Calculate
Close
Trial Cardiff
9.0.0.35 PhD
22:14
29/01/2021
ENG


C:\Users\Public\Documents\SimaPro\Database\Professional; H&M4 - [Analyze Conventional Villa (whole villa)]
File Edit Calculate Tools Window Help
Network
Tree
Impact assessment
Inventory
Process contribution
Setup
Checks (560)
Product overview
Characterization
Normalization
Skip categories
With result = 0
Standard
Group
Default units
Exclude long-term emissions
Per impact category
%
Global warming
Stratospheric ozone depleti
Ionizing radiation
Ozone formation, Human
Fine particulate matter form
Ozone formation, Terrestrial
Terrestrial acidification
Freshwater eutrophicatio
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicit
Human non-carcinogenic
Land use
Mineral resource scarcity
Fossil resource scarcity
AWARE
Conventional Villa (whole villa)
Bitumen adhesive compound, hot {RoW}| production | APOS, U
H Ceramic tile {RoW}| production | APOS, U
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U
H Bitumen seal {RoW}| production | APOS, U
H Door, inner, wood {RoW}| production | APOS, U
H Gypsum fibreboard {RoW}| production | APOS, U
H&M Cement mortar {RoW}| production | APOS, U
Method: ReCiPe 2016 Midpoint (H)_H&M=AWARE V1.03 / World (2010) H / Characterization
Analyzing 310 m2 'Conventional Villa (whole villa)';
Trial Cardiff
9.0.0.35 PhD
ENG
22:15
29/01/2021


C:\Users\Public\Documents\SimaPro\Database\Professional; H&M4 - [Compare Conventional Vi ..., Precast Villa, Standerd 3DP Vi ... and Innovative 3DP ...]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (560)
Product overview
Characterization
Normalization
Skip categories
With result = 0
Default units
Exclude long-term emissions
Per impact category
%
Global warming
Stratospheric ozone depleti
Ionizing radiation
Ozone formati on, Human
Fine particulat e matter form
Ozone formati on, Terrestrial
Terrestrial acidification
Freshwater eutrophicatio
Marine eutrop hication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcin ogenic toxicit
Human non -carcinogenic
Land use
Mineral resou rce scarcity
Fossil resourc e scarcity
AWARE
Conventional Villa (whole villa)
Precast Villa
Standerd 3DP Villa (whole villa) (Le et al 2012)
Innovative 3DP Villa (whole villa) (Le et al 2012)
Method: ReCiPe 2016 Midpoint (H)_H&M=AWARE V1.03 / World (2010) H / Characterization
Comparing 1 m2 'Conventional Villa (whole villa)', 1 m2 'Precast Villa', 1 m2 'Standerd 3DP Villa (whole villa) (Le et al 2012)' and 1 m2 'Innovative 3DP Villa (whole villa) (Le et al 2012)';
Trial Cardiff
9.0.0.35 PhD
ENG
22:16
29/01/2021

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Conventional Villa	310.16	m2	Area	100 %		!H&M\PhD work	

Add

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	93.81	kg	Undefined		Interior and Exterior
Bitumen adhesive compound, hot {RoW}| production | APOS, U	1771.90	kg	Undefined		bitumen foundation
H Bitumen seal {RoW}| production | APOS, U	1549.54	kg	Undefined		bitumen paint for roof
H Ceramic tile {RoW}| production | APOS, U	5079.84	kg	Undefined		Room tiles+bathroom and kitchen tiles for flooring and walls
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
H Gypsum fibreboard {RoW}| production | APOS, U	45.26	kg	Undefined		
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H&M Cement mortar {RoW}| production | APOS, U	61495.20	kg	Undefined		
H&M Concrete block {RoW}| production | APOS, U	6972.25	kg	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	5.74	m3	Undefined		formwork
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	29665.56	tkm	Undefined		concrete car empty
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	401.68	m3	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	152.80	kg	Undefined		foundation
Polystyrene foam slab {RoW}| production | APOS, U	1005.68	kg	Undefined		for roof and walls
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	507.6	kg	Undefined		water and swear pipes
Reinforcing steel {RoW}| production | APOS, U	52.72	ton	Undefined		

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| electricity production, oil | APOS, U	1755.26	kWh	Undefined				Concrete trcuk and Concrete pump

Add

Trial Cardiff 9.0.0.35 PhD

ENG 20:41 16/02/2021

Documentation | **Input/output** | Parameters | System description

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Conventional Villa (Sensitivity analysis)	310.16	m2	Area	100 %		!H&M\PhD work	
Add							

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	93.81	kg	Undefined		Interior and Exterior
Bitumen adhesive compound, hot {RoW}| production | APOS, U	313.19	kg	Undefined		bitumen foundation
H Bitumen seal {RoW}| production | APOS, U	1549.54	kg	Undefined		bitumen paint for roof
H Ceramic tile {RoW}| production | APOS, U	5079.84	kg	Undefined		Room tiles+bathroom and kitchen tiles for flooring and walls
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
H Gypsum fibreboard {RoW}| production | APOS, U	45.26	kg	Undefined		
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H&M Cement mortar {RoW}| production | APOS, U	61495.20	kg	Undefined		
H&M Concrete block {RoW}| production | APOS, U	6972.25	kg	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	8.1	m3	Undefined		formwork
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	20792.3	tkm	Undefined		concrete car empty
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	267.63	m3	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	152.80	kg	Undefined		foundation
Polystyrene foam slab {RoW}| production | APOS, U	1005.68	kg	Undefined		for roof and walls
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	507.6	kg	Undefined		water and swear pipes
Reinforcing steel {RoW}| production | APOS, U	35.13	ton	Undefined		
Add					

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| electricity production, oil | APOS, U	1169.49	kWh	Undefined				Concrete trcuk and Concrete pump
Add							

Trial Cardiff 9.0.0.35 PhD

20:42 ENG

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
H&M Cement, pozzolana and fly ash 23%, non-US {RoW}| production | APOS, U	30320.06	kg	Undefined		
Tap water {RoW}| tap water production, artificial recharged wells | APOS, U	9445.5	kg	Undefined		
Silica fume, densified {GLO}| silica fume, densified, Recycled Content cut-off | Cut-off, U	3400.38	kg	Undefined		
Polycarboxylates, 40% active substance {RoW}| production | APOS, U	661.19	kg	Undefined		
Fibre cement corrugated slab {RoW}| production | APOS, U	47.23	kg	Undefined		
H&M Sand {RoW}| gravel and quarry operation | APOS, U	50533.43	kg	Undefined		
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	137.358	tkm	Undefined		Transportation for KUKA KR robot
H Door, inner, wood {RoW}| production | APOS, U	33.03	m2	Undefined		
Reinforcing steel {RoW}| production | APOS, U	19.54	ton	Undefined		
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	212.32	m3	Undefined		62 is for the roof
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	4.27	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	37.6	m2	Undefined		
H Ceramic tile {RoW}| production | APOS, U	5895.64	kg	Undefined		room, kichen, and bathroom floors and walls
H Gypsum fibreboard {RoW}| production | APOS, U	37.76	kg	Undefined		
Polystyrene foam slab {RoW}| production | APOS, U	481.04	kg	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	147.91	kg	Undefined		
H Bitumen seal {RoW}| production | APOS, U	1346.93	kg	Undefined		roof
Bitumen adhesive compound, hot {RER}| production | APOS, U	1556.34	kg	Undefined		foundation
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	84.21	kg	Undefined		
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	507.6	kg	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	0.54	m3	Undefined		
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	18785.61	tkm	Undefined		transportation for all material and precast parts

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| production mix | APOS, U	1248.45	kWh	Undefined				
Electricity, high voltage {SA}| electricity production, oil | APOS, U	771.30	kWh	Undefined				

Add

Outputs

rial Cardiff 9.0.0.35 PhD

20:43

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
H&M Cement, pozzolana and fly ash 23%, non-US {RoW}| production | APOS, U	30320.06	kg	Undefined		
Tap water {RoW}| tap water production, artificial recharged wells | APOS, U	9445.5	kg	Undefined		
Silica fume, densified {GLO}| silica fume, densified, Recycled Content cut-off | Cut-off, U	3400.38	kg	Undefined		
Polycarboxylates, 40% active substance {RoW}| production | APOS, U	661.19	kg	Undefined		
Fibre cement corrugated slab {RoW}| production | APOS, U	47.23	kg	Undefined		
H&M Sand {RoW}| gravel and quarry operation | APOS, U	50533.43	kg	Undefined		
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	137.358	tkm	Undefined		Transportation for Cobod and its mixer and pump
H Door, inner, wood {RoW}| production | APOS, U	33.03	m2	Undefined		
Reinforcing steel {RoW}| production | APOS, U	18.38	ton	Undefined		Footing
Reinforcing steel {RoW}| production | APOS, U	1.16	ton	Undefined		Steel ties
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	212.32	m3	Undefined		62 is for the roof
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	4.27	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	37.6	m2	Undefined		
Epoxy resin, liquid {RoW}| production | APOS, U	30.50	kg	Undefined		room, kichen, and bathroom floors and walls
H Gypsum fibreboard {RoW}| production | APOS, U	37.76	kg	Undefined		
Polystyrene foam slab {RoW}| production | APOS, U	481.04	kg	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	147.91	kg	Undefined		
H Bitumen seal {RoW}| production | APOS, U	1346.93	kg	Undefined		roof
Bitumen adhesive compound, hot {RER}| production | APOS, U	1556.34	kg	Undefined		foundation
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	84.21	kg	Undefined		
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	507.6	kg	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	0.54	m3	Undefined		transport for other matiral without water and 3D concrete
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	18704.06	tkm	Undefined		transportation for all material and precast parts
Add					

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| production mix | APOS, U	1248.45	kWh	Undefined				
Electricity, high voltage {SA}| electricity production, oil | APOS, U	771.30	kWh	Undefined				
Add							

Outputs

rial Cardiff 9.0.0.35 PhD

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Precast Villa	310.16	m2	Area	100 %		!H&M\PhD work	
Add							

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	93.81	kg	Undefined		Interior and Exterior
Bitumen adhesive compound, hot {RoW}| production | APOS, U	1771.90	kg	Undefined		bitumen foundation
H Bitumen seal {RoW}| production | APOS, U	1549.54	kg	Undefined		bitumen paint for roof
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
H Gypsum fibreboard {RoW}| production | APOS, U	45.26	kg	Undefined		
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	0.81	m3	Undefined		formwork
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	32055.67	tkm	Undefined		
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	438.81	m3	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	152.80	kg	Undefined		foundation
Polystyrene foam slab {RoW}| production | APOS, U	730.56	kg	Undefined		for roof and walls
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	507.6	kg	Undefined		water and swear pipes
Reinforcing steel {RoW}| production | APOS, U	46.11	ton	Undefined		
Sheet rolling, steel {RoW}| processing | APOS, U	51.86	ton	Undefined		
Ceramic tile {RoW}| production | APOS, U	5079.84	kg	Undefined		
Add					

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| electricity production, oil | APOS, U	1972.43	kWh	Undefined				Concrete trcuk and Concrete pump
Add							

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Precast Villa (Sensitivity analysis)	310.16	m2	Area	100 %		!H&M\PhD work	
Add							

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	93.81	kg	Undefined		Interior and Exterior
Bitumen adhesive compound, hot {RoW}| production | APOS, U	1771.90	kg	Undefined		bitumen foundation
H Bitumen seal {RoW}| production | APOS, U	1549.54	kg	Undefined		bitumen paint for roof
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
H Gypsum fibreboard {RoW}| production | APOS, U	45.26	kg	Undefined		
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	0.81	m3	Undefined		formwork
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	31989.02	tkm	Undefined		
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	438.81	m3	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	152.80	kg	Undefined		foundation
Polystyrene foam slab {RoW}| production | APOS, U	730.56	kg	Undefined		for roof and walls
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	507.6	kg	Undefined		water and swear pipes
Reinforcing steel {RoW}| production | APOS, U	46.11	ton	Undefined		
Sheet rolling, steel {RoW}| processing | APOS, U	51.86	ton	Undefined		
Epoxy resin, liquid {RoW}| production | APOS, U	34.9	kg	Undefined		
Add					

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| electricity production, oil | APOS, U	1972.43	kWh	Undefined				Concrete trcuk and Concrete pump
Add							

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
Standard 3DP Villa	326.06	m2	Area	100 %		!H&M\PhD work	The functional unit here is 1x1x0.4 m load bearing external wall-unfinished ------ 50 MPa concrete is intended for structurally reinforced specialty usage, exposed to chlorides and other severe environments, with or without freezing and thawing conditions, and with high durability performances expectations (e.g. work of art etc.) (following the Canadian CSA specs -

Add

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
H&M Cement, pozzolana and fly ash 23%, non-US {RoW}| production | APOS, U	39107.67	kg	Undefined		(1,1,4,1,1,na) EcoSpold01Location=CH Including waste concrete. See Exchange Properties
Tap water {RoW}| tap water production, artificial recharged wells | APOS, U	12183.08	kg	Undefined		(1,1,4,1,1,na) EcoSpold01Location=CH Water use in ready-mix plant, assumed to be sourced from municipal water system. See Exchange properties comment for Sources.
Silica fume, densified {GLO}| silica fume, densified, Recycled Content cut-off | Cut-off, U	4385.91	kg	Undefined		
Polycarboxylates, 40% active substance {RoW}| production | APOS, U	852.82	kg	Undefined		
Fibre cement corrugated slab {RoW}| production | APOS, U	60.92	kg	Undefined		
H&M Sand {RoW}| gravel and quarry operation | APOS, U	65179.45	kg	Undefined		
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	38.506	tkm	Undefined		Transportation for KUKA KR robot
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
Reinforcing steel {RoW}| production | APOS, U	22.98	ton	Undefined		
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	229.31	m3	Undefined		62 is for the roof
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		

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Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	S	Comment
H&M Cement, pozzolana and fly ash 23%, non-US {RoW}| production | APOS, U	39107.67	kg	Undefined		(1,1,4,1,1,na) EcoSpold01Location=CH Including waste concrete. See Exchange Properties
Tap water {RoW}| tap water production, artificial recharged wells | APOS, U	12183.08	kg	Undefined		(1,1,4,1,1,na) EcoSpold01Location=CH Water use in ready-mix plant, assumed to be sourced from municipal water system. See Exchange properties comment for Sources.
Silica fume, densified {GLO}| silica fume, densified, Recycled Content cut-off | Cut-off, U	4385.91	kg	Undefined		
Polycarboxylates, 40% active substance {RoW}| production | APOS, U	852.82	kg	Undefined		
Fibre cement corrugated slab {RoW}| production | APOS, U	60.92	kg	Undefined		
H&M Sand {RoW}| gravel and quarry operation | APOS, U	65179.45	kg	Undefined		
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	38.506	tkm	Undefined		Transportation for KUKA KR robot
H Door, inner, wood {RoW}| production | APOS, U	26	m2	Undefined		
Reinforcing steel {RoW}| production | APOS, U	22.98	ton	Undefined		
HH&M Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only | APOS, U	229.31	m3	Undefined		62 is for the roof
H Window frame, aluminium, U=1.6 W/m2K {RoW}| production | APOS, U	3.24	m2	Undefined		
H Glazing, double, U<1.1 W/m2K, laminated safety glass {RoW}| production | APOS, U	23	m2	Undefined		
Epoxy resin, liquid {RER}| production | APOS, U	33.18	kg	Undefined		room, kichen, and bathroom floors and walls
H Gypsum fibreboard {RoW}| production | APOS, U	45.25	kg	Undefined		
Polystyrene foam slab {RoW}| production | APOS, U	469.60	kg	Undefined		
Polyethylene, high density, granulate {RoW}| production | APOS, U	159.68	kg	Undefined		
H Bitumen seal {RoW}| production | APOS, U	1546.88	kg	Undefined		roof
Bitumen adhesive compound, hot {RER}| production | APOS, U	1688.52	kg	Undefined		foundation
Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	93.43	kg	Undefined		
Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | APOS, U	507.6	kg	Undefined		
H&M Plywood, for outdoor use {RoW}| production | APOS, U	0.62	m3	Undefined		
Hashem Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	20205.22	tkm	Undefined		transportation for all material and precast parts

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Electricity, high voltage {SA}| production mix | APOS, U	1521.18	kWh	Undefined				
Electricity, high voltage {SA}| electricity production, oil | APOS, U	1053.73	kWh	Undefined				

Add

Appendix B

- **The English Version of the Questionnaire**

3D printing Technology in Construction

Page 1: Introduction

Dear Sir/Madam,

Recently, there has been an increased interest in the use of 3D printing technology as a new construction method for residential buildings around the world. This study aims to examine the potential for the adoption of 3D printing technology in the construction industry in Saudi Arabia.

The objectives of this study are:

- Investigate the attitude of Architects and Civil Engineers towards 3D printing technology in the Saudi Arabian construction sector.
- Assess the intentions of Architects and Civil Engineers to use 3D printing technology in their workplace.

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Page 2: Consent Form

1. All collected data from the questionnaire will be used for research purposes only. All personal information will be kept confidential. Furthermore, all the data will be used only by the researcher. Consent to proceed: please select your choice below. By clicking on the "Accept" button, you confirm that you are accepting to participate in this questionnaire. ✱ *Required*

- ○ Accept
- ○ Decline

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3D printing Technology in Construction

Page 1: Introduction

Dear Sir/Madam,

Recently, there has been an increased interest in the use of 3D printing technology as a new construction method for residential buildings around the world. This study aims to examine the potential for the adoption of 3D printing technology in the construction industry in Saudi Arabia.

The objectives of this study are:

- Investigate the attitude of Architects and Civil Engineers towards 3D printing technology in the Saudi Arabian construction sector.
- Assess the intentions of Architects and Civil Engineers to use 3D printing technology in their workplace.

Page 3: General information about the participant

2. What is your gender? * *Required*

- Male
- Female
- Prefer not to say

3. What is your age? * *Required*

- 18-34
- 35-49
- 50-64
- 65+
- Prefer not to say

4. What is your profession? * *Required*

- Architect
- Civil Engineer

5. What is your academic qualification? * *Required*

- Bachelor's degree
- Master's degree
- PhD
- Prefer not to say

6. Years of work experience? ✱ *Required*

- Less than 10 years
- From 10 to less than 20 years
- From 20 to less than 40 years.
- From 40 years and more.

7. Before participating in this survey, how far back were you aware that 3D printing technology can be used in the construction industry? ✱ *Required*

- I was not aware
- Up to 1 year ago
- In the past 1 to 5 years
- More than 5 years ago

8. Are you registered with the Saudi Council of Engineers SCE? ✱ *Required*

- Yes
- No

Page 4: Diffusion Innovation Theory

The survey is divided into five sections that represent the diffusion innovation theory of adopting new technology. Diffusion innovation theory was developed in 1962 by E.M. Rogers. This theory is considered to be one of the oldest social science theories. It studies the adoption of new technologies for users across each market and in different markets. Furthermore, this theory has five attributes that help to reduce uncertainty about innovation. These attributes are: relative advantage, complexity, compatibility, observability, and trialability.

Based on your experience and knowledge, you are asked to answer ALL the questions in ALL sections by entering scores on the 5-point Likert Scale **(Strongly disagree, Disagree, Neutral, Agree, Strongly agree)**. For each of the following statements, please indicate how much you agree with them.

Page 5: Relative Advantage

Relative advantage is "the degree to which an innovation is perceived as being better than the idea it supersedes" Rogers (2003).

9. 3D printing technology reduces the construction cost of a building. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

10. 3D printing technology reduces the construction time of a building. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

11. 3D printing technology reduces construction material waste. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

12. 3D printing technology can produce more complex shapes than other construction methods. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

13. 3D printing technology lowers overall construction life cycle environmental impacts. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

14. 3D printing technology improves the quality of construction. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

15. 3D printing technology enhances construction productivity. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

16. 3D printing technology improves the functionality of the finished building. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

Page 6: Complexity (Ease of use)

Complexity is "the degree to which an innovation is perceived as relatively difficult to understand and use" Rogers (2003).

17. 3D printing technology is easy to understand and use. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

18. Adopting 3D printing technology improves collaboration among architects, engineers, consultants, and contractors. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

19. Implementing 3D printing technology is a simple process. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree

○ 5 Strongly agree

20. Setting up 3D printing technology is clear and straightforward. ✱ *Required*

○ 1 Strongly disagree
○ 2 Disagree
○ 3 Neutral
○ 4 Agree
○ 5 Strongly agree

21. Finding employees who can operate 3D printers is easy. ✱ *Required*

○ 1 Strongly disagree
○ 2 Disagree
○ 3 Neutral
○ 4 Agree
○ 5 Strongly agree

22. It is easy to find experts to discuss and share their experience and knowledge of 3D printing technology. ✱ *Required*

○ 1 Strongly disagree
○ 2 Disagree
○ 3 Neutral
○ 4 Agree
○ 5 Strongly agree

Page 7: Compatibility

Compatibility is “the degree to which an innovation is perceived as consistent with the existing values, past experience, and needs of potential adopters” Rogers (2003).

23. 3D printing technology is consistent with needs of my workplace. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

24. My workplace has already investigated 3D printing technology. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

25. My workplace intents to provide seminars and workshops on 3D printing technology. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree

- 5 Strongly agree

26. The materials used in 3D printing technology are compatible with conventional construction. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

27. 3D printing technology is compatible with a construction site environment. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

28. 3D printing technology has the flexibility to print various sizes of objects for different construction needs. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

Page 8: Observability

Observability is "the degree to which the results of an innovation are visible to others" Rogers (2003).

29. I have observed how 3D Printing technology is faster than traditional construction. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

30. I have observed how 3D Printing technology is more effective than traditional construction. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

31. I have observed how 3D Printing technology gives greater control over work quality parameters. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree

- 3 Neutral
- 4 Agree
- 5 Strongly agree

32. I have observed how 3D printing technology is more economical than conventional construction methods. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

33. I have observed 3D printing technology produces aesthetically more pleasing results. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

34. I have observed 3D printing technology offers a competitive advantage to a company. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral

- 4 Agree
- 5 Strongly agree

Page 9: Trialability

Trialability is "the degree to which an innovation may be experimented with on a limited basis" Rogers (2003).

35. Before deciding whether to use 3D Printing technology in construction or not, my workplace would need to trial the process and technology. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

36. My workplace would adopt 3D printing technology only if other companies or firms started using it. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

37. The ability to try 3D printing technology before adoption provides the possibility of risk reduction. ✱ *Required*

- 1 Strongly disagree
- 2 Disagree

- 3 Neutral
- 4 Agree
- 5 Strongly agree

38. 3D printing technology building codes and regulations should be accredited before trying the technology. * *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

39. My firm will experiment with 3D peinting technology in the next 5 years. * *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral
- 4 Agree
- 5 Strongly agree

40. There are many hurdles to overcome before my workplace can experiment with 3D printing technology. * *Required*

- 1 Strongly disagree
- 2 Disagree
- 3 Neutral

○ 4 Agree

○ 5 Strongly agree

Page 10: Submission

Thank you for taking the time to complete this questionnaire.

For further information regarding Diffusion of Innovations Theory:

Rogers, E.M. (2003). Diffusion of innovations (5th ed.). New York: Free Press.

About the researcher:

Hashem Alhumayani

PhD candidate

Computational Architecture

Welsh School of Architecture

Cardiff University

Bute Building, King Edward VII Avenue

Cardiff, CF10 3NB

Phone: +44 (0) 7462207943

+966 (0) 545222287

E-mail: Alhumayanih@cardiff.ac.uk

Supervisor:

Wassim Jabi, PhD Reader – Computational Methods in Architecture

Welsh School of Architecture

Cardiff University

Bute Building

King Edward VII Avenue

Cardiff CF10 3NB

Wales U.K.

E-mail: jabiw@cardiff.ac.uk

- **The Arabic Version of the Questionnaire**

تقنية الطباعة ثلاثية الأبعاد في البناء

Page 1: مقدمة

عزيزي السيد / السيدة

في الآونة الأخيرة ، لوحظ ان هنالك اهتمام متزايد لاستخدام تقنية الطباعة ثلاثية الأبعاد كطريقة بناء جديدة للمباني السكنية حول العالم .

تهدف هذه الدراسة إلى دراسة إمكانية اعتماد تقنية الطباعة ثلاثية الأبعاد في قطاع البناء والتشييد في المملكة العربية السعودية

أهداف هذه الدراسة

التحقق من موقف المعماريين والمهندسين المدنيين تجاه تقنية الطباعة ثلاثية الأبعاد في قطاع البناء والتشييد في المملكة العربية السعودية.

دراسة إمكانية استخدام تقنية الطباعة ثلاثية الأبعاد في أماكن عمل المعماريين والمهندسين المدنيين.

Page 2: نموذج الموافقة

1. سيتم استخدام جميع البيانات التي تم جمعها من الاستبيان لأغراض البحث فقط. ستبقى جميع المعلومات الشخصية سرية. علاوة على ذلك ، سيتم استخدام جميع البيانات من قبل الباحث فقط. للموافقة على المتابعة: الرجاء تحديد اختيارك أدناه. بالنقر فوق الزر "قبول" ، فإنك تؤكد قبولك للمشاركة في هذا الاستبيان *Required*

- ○ قبول
- ○ رفض

Page 3: معلومات عامة عن المشارك

2. الجنس؟ ✱ Required

- ذكر
- أنثى
- أفضل عدم الإجابة

3. العمر؟ ✱ Required

- 18-34
- 35-49
- 50-64
- 65+
- أفضل عدم الاجابة

4. ما هي مهنتك؟ ✱ Required

- معماري
- مهندس مدني

5. المؤهلات الأكاديمية؟ ✱ Required

- بكالوريوس
- ماجستير
- دكتوراه
- أفضل عدم الإجابة

6. عدد سنوات الخبرة ✱ Required

- أقل من ١٠ سنوات
- من 10 الى اقل من 20 سنة
- من 20 الى اقل من 40 سنة
- من 40 سنة فأكثر

7. قبل المشاركة في هذا الاستطلاع ، إلى أي مدى كنت تدرك أن تقنية الطباعة ثلاثية الأبعاد يمكن استخدامها في قطاع البناء ✱ Required

- لم أكن على علم بهذه التقنية
- سنة
- من سنة إلى 5 سنوات
- أكثر من 5 سنوات

8. هل أنت مسجل في الهيئة السعودية للمهندسين؟ ✱ Required

- نعم
- لا

Page 4: نظرية انتشار الابتكار

ينقسم هذا الاستبيان إلى خمسة أقسام والتي تمثل نظرية انتشار الابتكار لتبني التكنولوجيا الجديدة. تم تطوير هذه النظرية في عام 1962 بواسطة E.M. Rogers.

تعتبر هذه النظرية من أقدم نظريات العلوم الاجتماعية. هذه النظرية تدرس اعتماد تقنيات جديدة للمستخدمين عبر كل سوق وفي أسواق مختلفة. علاوة على ذلك ، تحتوي هذه النظرية على خمس سمات تساعد في تقليل عدم التأكد من الابتكارات الجديدة . هذه السمات هي: الميزة النسبية ، التعقيد ، التوافق ، قابلية الملاحظة وقابلية التجربة

بناءً على خبرتك ومعرفتك ، يُطلب منك الإجابة على جميع الأسئلة في جميع الأقسام عن طريق إدخال الدرجات على مقياس ليكرت المكون من 5 نقاط (لا أوافق بشدة ، لا أوافق ، محايد ، أوافق ، أوافق بشدة). لكل من العبارات التالية ، يرجى الإشارة إلى مدى موافقتك عليها

Page 5: الميزة النسبية

المِيزة النسبية هي "الدرجة التي يُنظر فيها إلى الابتكار على أنه أفضل من الفكرة التي يحل محلها" روجرز (2003

9. تقلل تقنية الطباعة ثلاثية الأبعاد من تكلفة تشييد المبنى * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

10. تقنية الطباعة ثلاثية الأبعاد تقلل من الوقت المستهلك لتشييد المبنى * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

11. تقلل تقنية الطباعة ثلاثية الأبعاد من نفايات البناء * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

12. يمكن أن تنتج تقنية الطباعة ثلاثية الأبعاد أشكالًا أكثر تعقيدًا من طرق البناء الأخرى ✱ Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

13. تقلل تقنية الطباعة ثلاثية الأبعاد من التأثيرات البيئية لدورة حياة المبنى ✱ Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

14. تعمل تقنية الطباعة ثلاثية الأبعاد على تحسين جودة البناء ✱ Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

15. تعزز تقنية الطباعة ثلاثية الأبعاد من إنتاجية البناء ✱ Required

- لا أوافق بشدة 1

- 2 لا أوافق
- 3 محايد
- 4 أوافق
- 5 أوافق بشدة

16. تعمل تقنية الطباعة ثلاثية الأبعاد على تحسين وظائف المبنى النهائية ✱ Required

- 1 لا أوافق بشدة
- 2 لا أوافق
- 3 محايد
- 4 أوافق
- 5 أوافق بشدة

Page 6: التعقيد (سهولة الاستخدام)

التعقيد هو "الدرجة التي يُنظر فيها إلى الابتكار على أنه من الصعب نسبيًا فهمه واستخدامه" روجرز (2003)

17. تقنية الطباعة ثلاثية الأبعاد سهلة الفهم والاستخدام * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

18. يؤدي اعتماد تقنية الطباعة ثلاثية الأبعاد إلى تحسين التعاون بين المعماريين والمهندسين والاستشاريين والمقاولين * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

19. يعد تنفيذ تقنية الطباعة ثلاثية الأبعاد عملية بسيطة * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

20. يُعد إعداد تقنية الطباعة ثلاثية الأبعاد أمرًا واضحًا ومباشرًا * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

21. من السهل العثور على موظفين يمكنهم تشغيل الطابعات ثلاثية الأبعاد * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

22. من السهل العثور على خبراء لمناقشة وتبادل خبراتهم ومعرفتهم بتقنية الطباعة ثلاثية الأبعاد * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

Page 7: التوافق

التوافق هو "الدرجة التي يُنظر فيها إلى الابتكار على أنه متوافق مع القيم الحالية والخبرة السابقة واحتياجات المتبنين المحتملين" روجرز (2003)

23. تتوافق تقنية الطباعة ثلاثية الأبعاد مع احتياجات مكان عملي * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

24. لقد قام عملي بالدراسة والتحقيق عن تقنية الطباعة ثلاثية الأبعاد * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

25. ينوي مكان عملي تقديم ندوات وورش عمل حول تقنية الطباعة ثلاثية الأبعاد * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

26. المواد المستخدمة في تقنية الطباعة ثلاثية الأبعاد متوافقة مع البناء التقليدي * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

27. تقنية الطباعة ثلاثية الأبعاد متوافقة مع بيئة موقع البناء * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

28. تتمتع تقنية الطباعة ثلاثية الأبعاد بالمرونة في طباعة أحجام مختلفة من الوحدات لتلبية احتياجات البناء المختلفة * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

Page 8: قابلية الملاحظة

الملاحظة هي "الدرجة التي تظهر بها نتائج الابتكار للآخرين" روجرز (2003)

29. لقد لاحظت كيف أن تقنية الطباعة ثلاثية الأبعاد أسرع من البناء التقليدي * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

30. لقد لاحظت كيف أن تقنية الطباعة ثلاثية الأبعاد أكثر فعالية من البناء التقليدي * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

31. لقد لاحظت كيف تمنح تقنية الطباعة ثلاثية الأبعاد تحكمًا أكبر في معايير جودة العمل * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

32. لقد لاحظت كيف أن تقنية الطباعة ثلاثية الأبعاد أكثر اقتصادا من طرق البناء التقليدية * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

33. لقد لاحظت أن نتائج تقنية الطباعة ثلاثية الأبعاد تكون أكثر إرضاء من الناحية الجمالية * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

34. لقد لاحظت أن تقنية الطباعة ثلاثية الأبعاد توفر ميزة تنافسية للشركة * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

Page 9: قابلية التجربة

قابلية التجربة هي "الدرجة التي يمكن بها تجربة الابتكار على أساس محدود" روجرز (2003)

35. قبل اتخاذ القرار بشأن استخدام تقنية الطباعة ثلاثية الأبعاد في البناء أم لا ، سيحتا ج مكان عملي إلى تجربة عملية للتقنية * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

36. سيتم تبني تقنية الطباعة ثلاثية الأبعاد في مكان عملي فقط إذا بدأت المكاتب الهندسية أو الشركات الأخرى في استخدامها * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4
- أوافق بشدة 5

37. القدرة على تجربة تقنية الطباعة ثلاثية الأبعاد قبل التبني سوف يساعد في تقليل المخاطر. * Required

- لا أوافق بشدة 1
- لا أوافق 2
- محايد 3
- أوافق 4

5 أوافق بشدة

38. يجب اعتماد قوانين ولوائح للبناء بتقنية الطباعة ثلاثية الأبعاد قبل تجربة التقنية * Required

- 1 لا أوافق بشدة
- 2 لا أوافق
- 3 محايد
- 4 أوافق
- 5 أوافق بشدة

39. سيقوم مكان عملي بتجربة تقنية الطباعة ثلاثية الأبعاد في السنوات الخمس القادمة * Required

- 1 لا أوافق بشدة
- 2 لا أوافق
- 3 محايد
- 4 أوافق
- 5 أوافق بشدة

40. هناك العديد من العقبات التي يجب التغلب عليها قبل أن يتمكن مكان عملي من تجربة تقنية الطباعة ثلاثية الأبعاد * Required

- 1 لا أوافق بشدة
- 2 لا أوافق
- 3 محايد
- 4 أوافق
- 5 أوافق بشدة

Page 10: التقديم

شكرًا لك على الوقت الذي قضيته في إكمال هذا الاستبيان

لمزيد من المعلومات حول نظرية انتشار الابتكارات

Rogers, E.M. (2003). Diffusion of innovations (5th ed.). New York: Free Press.

هاشم الحمياني

باحث دكتوراه

كلية العمارة، ويلز ، المملكة المتحدة

جامعة كارديف

البريد الإلكتروني Alhumayanih@cardiff.ac.uk

المشرف الدراسي

الدكتور وسيم جابي

البريد الإلكتروني : jabiw@cardiff.ac.uk

- **Validation of Translation**

استبيان للمعماريين والمهندسين المدنيين (النسخة العربية)

الصفحة ١: مقدمة

عزيزي السيد / السيدة، في الأونة الأخيرة ، لوحظ ان هنالك اهتمام متزايد لاستخدام تقنية الطباعة ثلاثية الأبعاد كطريقة بناء جديدة للمباني السكنية حول العالم.

تهدف هذه الدراسة إلى دراسة إمكانية اعتماد تقنية الطباعة ثلاثية الأبعاد في قطاع البناء في المملكة العربية السعودية

أهداف هذه الدراسة:

التحقق من موقف المهندسين المعماريين والمدنيين تجاه تقنية الطباعة ثلاثية الأبعاد في قطاع البناء والتشييد في المملكة العربية السعودية.

دراسة إمكانية استخدام تقنية الطباعة ثلاثية الأبعاد في أماكن عملهم المهندسين المعماريين المدنيين لإستخدام تقنية الطباعة ثلاثية الأبعاد في أماكن عملهم.

تقييم أي قطاعات البناء التي يرى المعماريون والمدنيون أنها من المرجح أن تتبنى تقنية الطباعة ثلاثية الأبعاد كطريقة بناء جديدة.

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الصفحة ٢: نموذج الموافقة

سيتم استخدام جميع البيانات التي تم جمعها من الاستبيان لأغراض البحث فقط. ستبقى جميع المعلومات الشخصية سرية. علاوة على ذلك ، سيتم استخدام جميع البيانات من قبل الباحث فقط.

الموافقة على المتابعة: الرجاء تحديد اختيارك أدناه. بالنقر فوق الزر "قبول" ، فإنك تؤكد قبولك للمشاركة في هذا الاستبيان.

☐ قبول ☐ رفض

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الصفحة ٣: معلومات عامة عن المشارك :

الجنس؟

☐ ذكر ☐ أنثى ☐ أفضل عدم الإجابة

العمر؟

☐ ١٨-٢٤ ☐ ٣٥-٤٩ ☐ ٥٠-٦٤ ☐ ٦٥+ ☐ أفضل عدم الإجابة

ما هي مهنتك؟

☐ مهندس معماري ☐ مهندس مدني

المؤهلات الأكاديمية:

☐ بكالوريوس ☐ ماجستير ☐ دكتوراه ☐ أفضل عدم الإجابة

عدد سنوات الخبرة

☐ أقل من ١٠ سنوات ☐ من ١٠ الى اقل من ٢٠ سنة

☐ من ٢٠ الى اقل من ٤٠ سنة ☐ من ٤٠ سنة فاكثر

قبل المشاركة في هذا الاستطلاع ، إلى أي مدى كنت تدرك أن تقنية الطباعة ثلاثية الأبعاد يمكن استخدامها في قطاع البناء

☐ لم أكن على علم بهذه التقنية ☐ سنة

☐ من سنة إلى ٥ سنوات ☐ أكثر من ٥ سنوات

هل انت مسجل في الهيئة السعودية للمهندسين؟

☐ نعم ☐ لا

الصفحة ٤: نظرية انتشار الابتكار

ينقسم هذا الاستبيان إلى خمسة أقسام والتي تمثل نظرية انتشار الابتكار لتبني التكنولوجيا الجديدة. تم تطوير هذه النظرية في عام ١٩٦٢ بواسطة E.M. Rogers.

تعتبر هذه النظرية من أقدم نظريات العلوم الاجتماعية. هذه النظرية تدرس اعتماد تقنيات جديدة للمستخدمين عبر كل سوق وفي أسواق مختلفة. علاوة على ذلك ، تحتوي هذه النظرية على خمس سمات تساعد في تقليل عدم التاكد من الابتكارات الجديدة . هذه السمات هي: الميزة النسبية ، التعقيد ، التوافق ، قابلية الملاحظة وقابلية التجربة

بناءً على خبرتك ومعرفتك ، يُطلب منك الإجابة على جميع الأسئلة في جميع الأقسام عن طريق إدخال الدرجات على مقياس ليكرت المكون من ٥ نقاط (لا أوافق بشدة ، لا أوافق ، محايد ، أوافق ، أوافق بشدة). لكل من العبارات التالية ، يرجى الإشارة إلى مدى موافقتك عليها.

الصفحة ٥: الميزة النسبية

تقلل تقنية الطباعة ثلاثية الأبعاد من تكلفة تشييد المبنى

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تقنية الطباعة ثلاثية الأبعاد تقلل من الوقت المستهلك لتشييد المبنى

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تقلل تقنية الطباعة ثلاثية الأبعاد من نفايات البناء

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

يمكن أن تنتج تقنية الطباعة ثلاثية الأبعاد أشكالًا أكثر تعقيداً من طرق البناء الأخرى

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تقلل تقنية الطباعة ثلاثية الأبعاد من التأثيرات البيئية لدورة حياة المبنى

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تعمل تقنية الطباعة ثلاثية الأبعاد على تحسين جودة البناء

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تعزز تقنية الطباعة ثلاثية الأبعاد إنتاجية البناء

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تعمل تقنية الطباعة ثلاثية الأبعاد على تحسين وظائف المبنى النهائية

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

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الصفحة ٦: التعقيد (سهولة الاستخدام)

التعقيد هو "الدرجة التي يُنظر فيها إلى الابتكار على أنه من الصعب نسبيًا فهمه واستخدامه" روجرز(2003)

تقنية الطباعة ثلاثية الأبعاد سهلة الفهم والاستخدام

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

يؤدي اعتماد تقنية الطباعة ثلاثية الابعاد إلى تحسين التعاون بين المعماريين والمهندسين والاستشاريين والمقاولين.

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

يعد تنفيذ تقنية الطباعة ثلاثية الأبعاد عملية بسيطة

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

يُعد إعداد تقنية الطباعة ثلاثية الأبعاد أمرًا واضحًا ومباشرًا

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

من السهل العثور على موظفين يمكنهم تشغيل الطابعات ثلاثية الأبعاد

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

من السهل العثور على خبراء لمناقشة وتبادل خبراتهم ومعرفتهم بتقنية الطباعة ثلاثية الأبعاد

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

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الصفحة ٧: التوافق

التوافق هو "الدرجة التي يُنظر فيها إلى الابتكار على أنه متوافق مع القيم الحالية والخبرة السابقة واحتياجات المتبنين المحتملين" روجرز(2003)

تتوافق تقنية الطباعة ثلاثية الأبعاد مع احتياجات مكان عملي

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

لقد قام مكان عملي بالدراسة والتحقق عن تقنية الطباعة ثلاثية الابعاد

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

ينوي مكان عملي تقديم ندوات وورش عمل حول تقنية الطباعة ثلاثية الابعاد

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

المواد المستخدمة في تقنية الطباعة ثلاثية الأبعاد متوافقة مع البناء التقليدي

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تقنية الطباعة ثلاثية الأبعاد متوافقة مع بيئة موقع البناء

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

تتمتع تقنية الطباعة ثلاثية الأبعاد بالمرونة في طباعة أحجام مختلفة من الوحدات لتلبية احتياجات البناء المختلفة

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

الصفحة ٨: قابلية الملاحظة

الملاحظة هي "الدرجة التي تظهر بها نتائج الابتكار للآخرين" روجرز(2003)

لقد لاحظت كيف أن تقنية الطباعة ثلاثية الأبعاد أسرع من البناء التقليدي

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

لقد لاحظت كيف أن تقنية الطباعة ثلاثية الأبعاد أكثر فعالية من البناء التقليدي

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

لقد لاحظت كيف تمنح تقنية الطباعة ثلاثية الأبعاد تحكمًا أكبر في معايير جودة العمل

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

لقد لاحظت كيف أن تقنية الطباعة ثلاثية الأبعاد أكثر اقتصادا من طرق البناء التقليدية

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

لقد لاحظت أن نتائج تقنية الطباعة ثلاثية الأبعاد تكون أكثر إرضاء من الناحية الجمالية

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

لقد لاحظت أن تقنية الطباعة ثلاثية الأبعاد توفر ميزة تنافسية للشركة

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

الصفحة ٩: قابلية التجربة

قابلية التجربة هي "الدرجة التي يمكن بها تجربة الابتكار على أساس محدود" روجرز (2003)

قبل اتخاذ القرار بشان استخدام تقنية الطباعة ثلاثية الأبعاد في البناء أم لا ، سيحتاج مكان عملي إلى تجربة عملية للتقنية

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

سيتبنى مكان عملي تقنية الطباعة ثلاثية الأبعاد فقط إذا بدأت المكاتب الهندسية أو الشركات الأخرى في استخدامها

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

القدرة على تجربة تقنية الطباعة ثلاثية الأبعاد قبل التبني سوف يساعد في تقليل المخاطر.

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

يجب اعتماد قوانين ولوائح للبناء بتقنية الطباعة ثلاثية الأبعاد قبل تجربة التقنية

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

سيقوم مكان عملي بتجربة تقنية الطباعة ثلاثية الأبعاد في السنوات الخمس القادمة

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

هناك العديد من العقبات التي يجب التغلب عليها قبل أن يتمكن مكان عملي من تجربة تقنية الطباعة ثلاثية الأبعاد

☐ لا أوافق بشدة ☐ لا أوافق ☐ محايد ☐ أوافق ☐ أوافق بشدة

الصفحة ١٠: التقديم

شكراً لك على الوقت الذي قضيته في إكمال هذا الاستبيان

لمزيد من المعلومات حول نظرية انتشار الابتكارات:

Rogers, E.M. (2003). Diffusion of innovations (5th ed.). New York: Free Press.

هاشم الحمياني

باحث دكتوراه

كلية العمارة، ويلز، المملكة المتحدة

جامعة كارديف

البريد الإلكتروني:Alhumayanih@cardiff.ac.uk

المشرف الدراسي

الدكتور وسيم جابي

البريد الإلكتروني :jabiw@cardiff.ac.uk

مكتب معتوق الثمالي للترجمة
ترخيص رقم ٥٨٩
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معتوق جابر الثمالي

- Ethics Form

WELSH SCHOOL OF ARCHITECTURE
ETHICS APPROVAL FORM FOR STAFF AND PHD/MPHIL PROJECTS

Tick one box:	☐ STAFF ■ PHD/MPHIL
Title of project:	**The Feasibility of 3D Printing Technology as a New Construction Method For Houses in Saudi Arabia** (Environmental and Social Study)
Name of researcher(s):	Hashem Alhumayani
Name of principal investigator	
Contact e-mail address:	alhumayanih@cardiff.ac.uk
Date:	30-11-2020

Participants		YES	NO	N/A
Does the research involve participants from any of the following groups?	• Children (under 16 years of age)		✓	
	• People with learning difficulties		✓	
	• Patients (NHS approval is required)		✓	
	• People in custody		✓	
	• People engaged in illegal activities		✓	
	• Vulnerable elderly people		✓	
	• Any other vulnerable group not listed here		✓	
• When working with children: I have read the Interim Guidance for Researchers Working with Children and Young People (http://www.cardiff.ac.uk/archi/ethics_committee.php)		✓		

Consent Procedure	YES	NO	N/A
• Will you describe the research process to participants in advance, so that they are informed about what to expect?	✓		
• Will you tell participants that their participation is voluntary?	✓		
• Will you tell participants that they may withdraw from the research at any time and for any reason?	✓		
• Will you obtain valid consent from participants? (specify how consent will be obtained in Box A)[1]	✓		
• Will you give participants the option of omitting questions they do not want to answer?	✓		
• If the research is observational, will you ask participants for their consent to being observed?			✓
• If the research involves photography or other audio-visual recording, will you ask participants for their consent to being photographed / recorded and for its use/publication?			✓

Possible Harm to Participants	YES	NO	N/A
• Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		✓	
• Is there any realistic risk of any participants experience a detriment to their interests as a result of participation?		✓	

Data Protection		YES	NO	N/A
• Will any non-anonymous and/or personalised data be generated or stored?			✓	
• If the research involves non-anonymous and/or personalised data, will you:	• gain written consent from the participants	✓		
	• allow the participants the option of anonymity for all or part of the information they provide	✓		

Health and Safety	YES
Does the research meet the requirements of the University's Health & Safety policies? (http://www.cf.ac.uk/osheu/index.html)	✓

Research Governance	YES	NO	N/A
Does your study include the use of a drug? You need to contact Research Governance before submission (resgov@cf.ac.uk)		✓	✓
Does the study involve the collection or use of human tissue? You need to contact the Human Tissue Act team before submission (hta@cf.ac.uk)		✓	✓

[1] If any non-anonymous and/or personalised data be generated or stored, *written consent* is required.

Prevent Duty	YES	
Has due regard be given to the 'Prevent duty', in particular to prevent anyone being drawn into terrorism? https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/445916/Prevent_Duty_Guidance_For_Higher_Education__England__Wales_.pdf http://www.cardiff.ac.uk/publicinformation/policies-and-procedures/freedom-of-speech	✓	

If any of the shaded boxes have been ticked, you must explain in Box A how the ethical issues are addressed. If none of the boxes have been ticked, you must still provide the following information. The list of ethical issues on this form is not exhaustive; if you are aware of any other ethical issues you need to make the SREC aware of them.

Box A **The Project** (provide all the information listed below in a separate attachment)

1. Title of Project

   The Feasibility of 3D Printing Technology as a New Construction Method For Houses in Saudi Arabia
   (Environmental and Social Study)

2. Purpose of the project and its academic rationale
   The study aims to examine the potential for the adoption of 3D printing technology in the construction industry in Saudi Arabia.

3. Brief description of methods and measurements
   The study will be done under quantitative method using a set of questions sent online through Bristol online survey. After receiving the answers there will be an analysis to the answers with SPSS.

4. Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria
   * The study will take place in Saudi Arabia and the participants will be Architects and Civil Engineers that works in Saudi Arabia.
   * The questionnaire will be sent online through email and social media.
   * The participants of this questionnaire will be from both males and females.
   * The age of the participants will be from 18 to +65.

5. Consent and participation information arrangements - please attached consent forms if they are to be used.
   Attached with the form.

6. A clear and concise statement of the ethical considerations raised by the project and how is dealt with them
   * There will be a description at the beginning of the questionnaire about the reason for the questionnaire and that the answers and identity of the participant will be kept from public.

7. Estimated start date and duration of project
   * 10-12-2020 and it will continue till we reach the sample size.

All information must be submitted along with this form to the School Research Ethics Committee for consideration

Researcher's declaration (tick as appropriate)	
• I consider this project to have **negligible ethical implications** (*can only be used if none of the grey areas of the checklist have been ticked*).	✓
• I consider this project research to have **some ethical implications**.	
• I consider this project to have **significant ethical implications**	

Signature **Name: Hashem Alhumayani** **Date 30-11-2020**
Researcher or MPhil/PhD student

Wassim
Signature **Name: Dr. Wassim Jabi** **Date 30-11-2020**
Lead investigator or supervisor

Advice from the School Research Ethics Committee

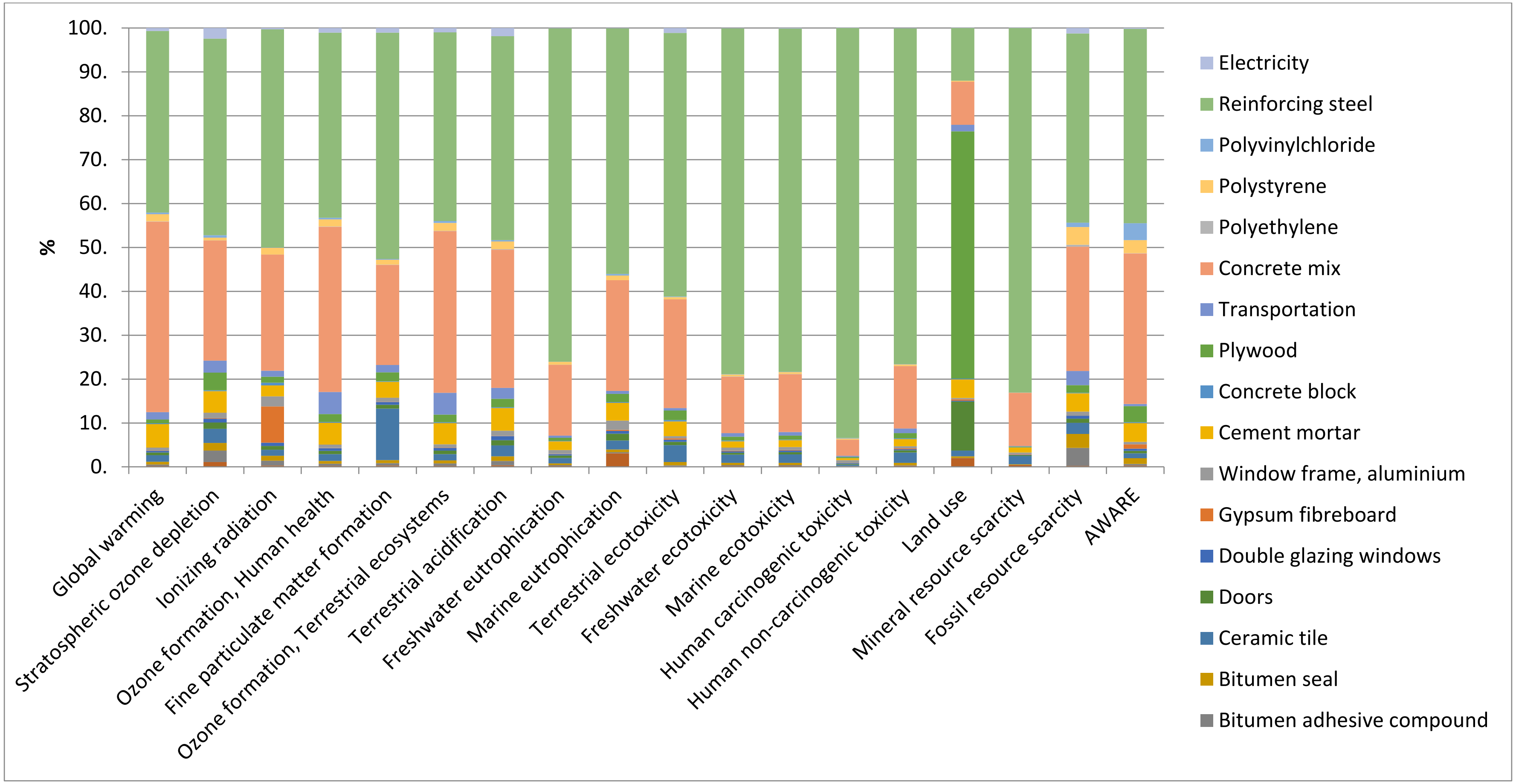
STATEMENT OF ETHICAL APPROVAL

This project had been considered using agreed Departmental procedures and is now approved

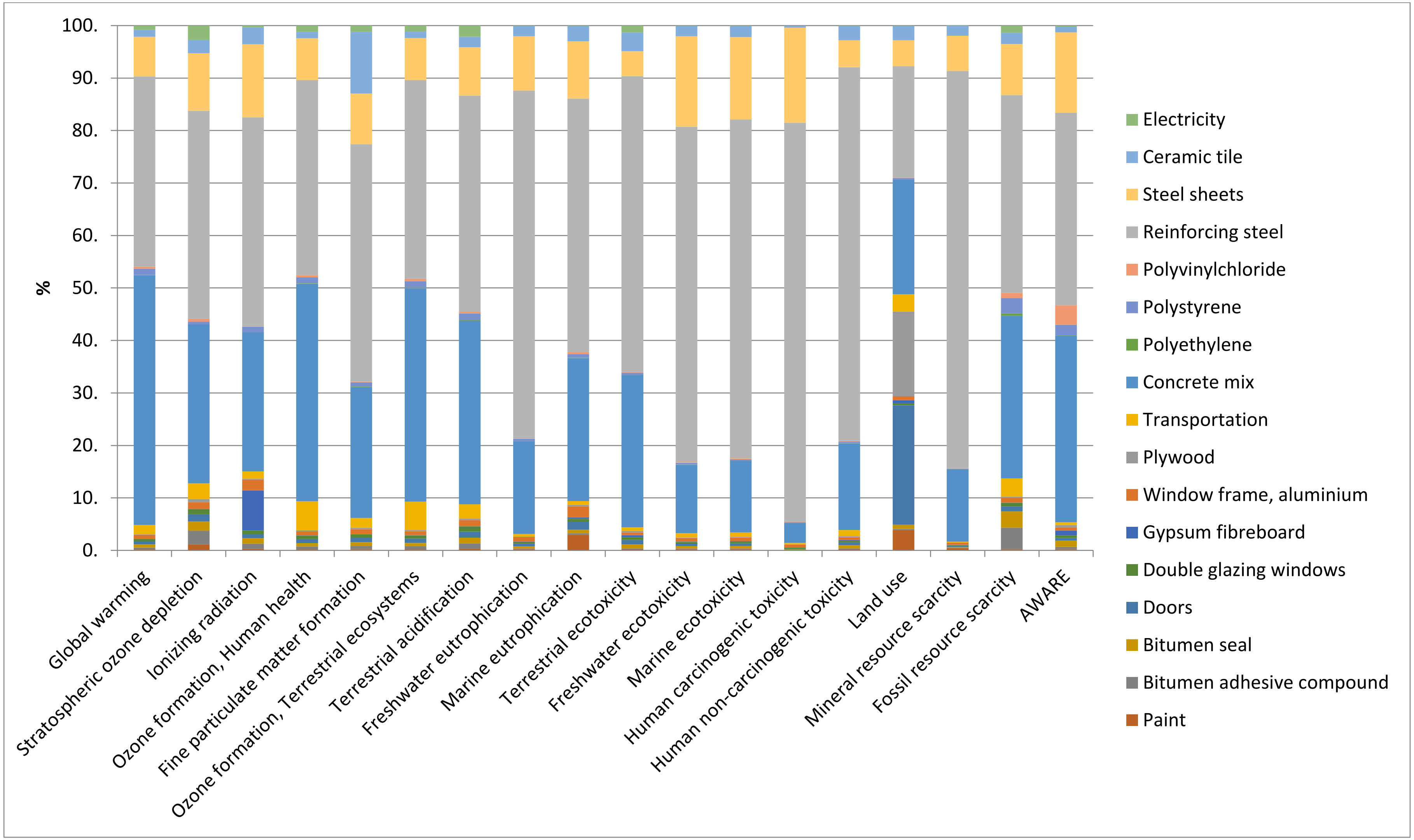
Signature **Name** Dr Chris Whitman **Date** 03/12/20
Chair, School Research Ethics Committee

Appendix C

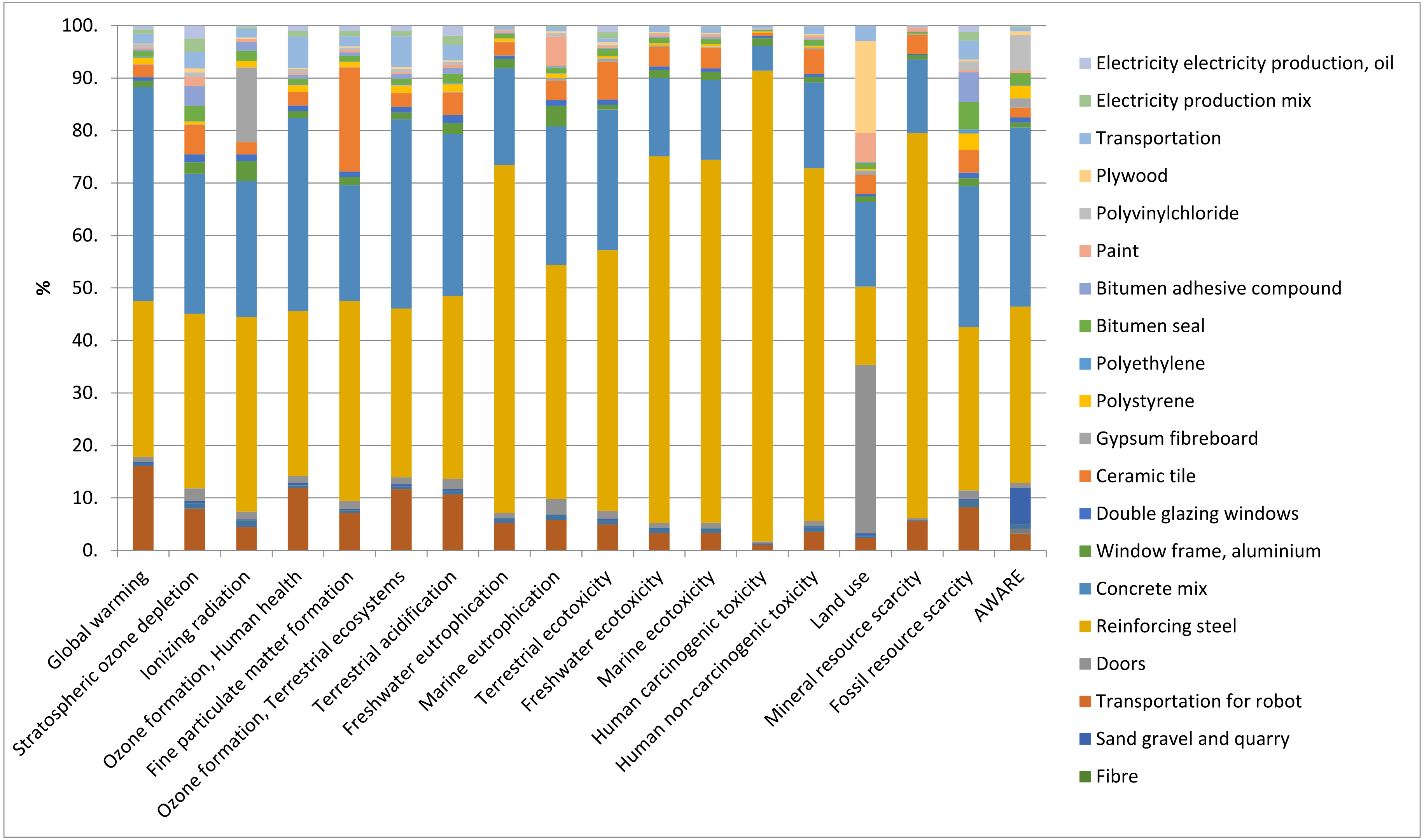
- **18 factors for Conventional Villa**



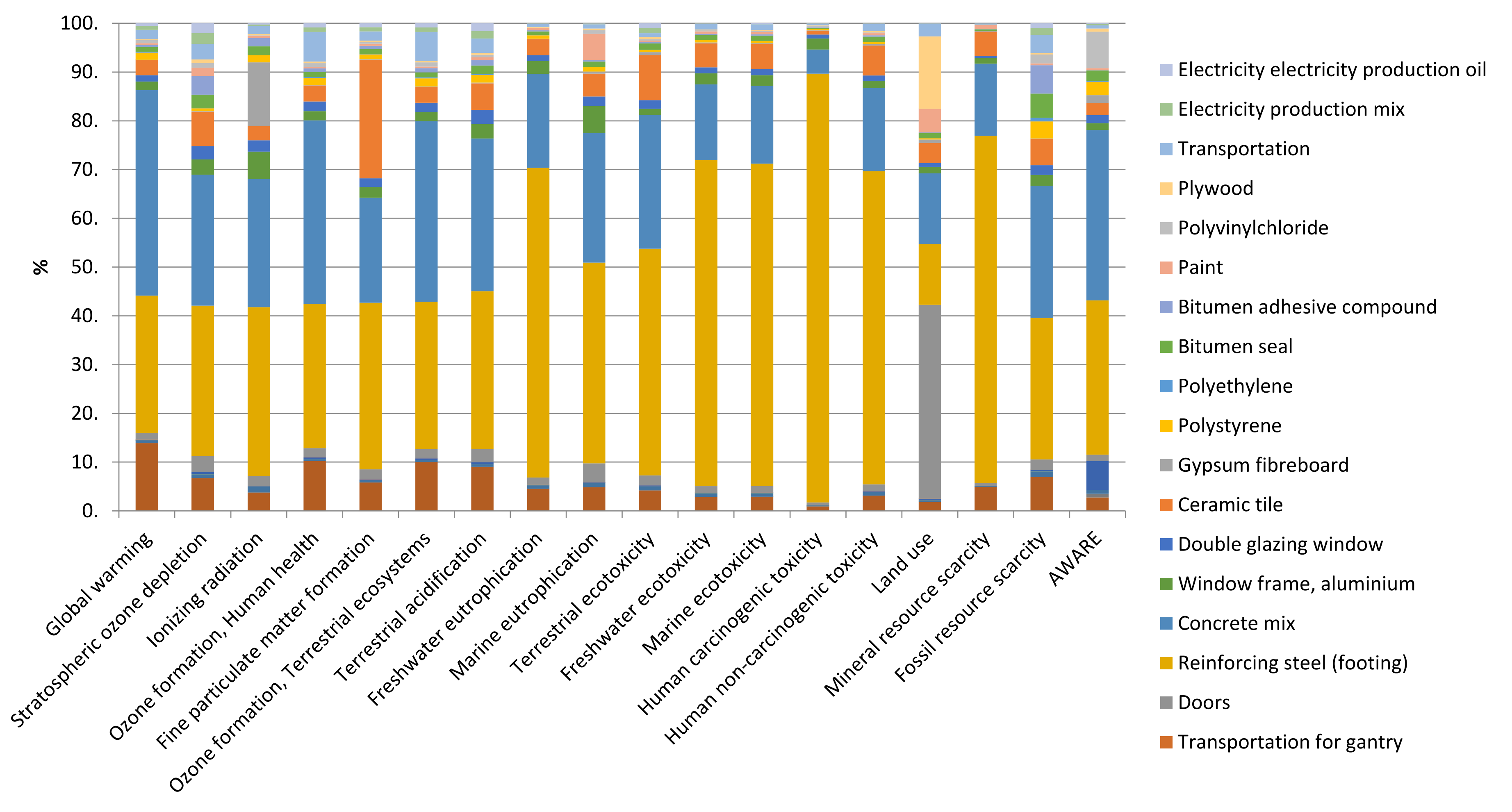
- **18 factors for Precast Villa**



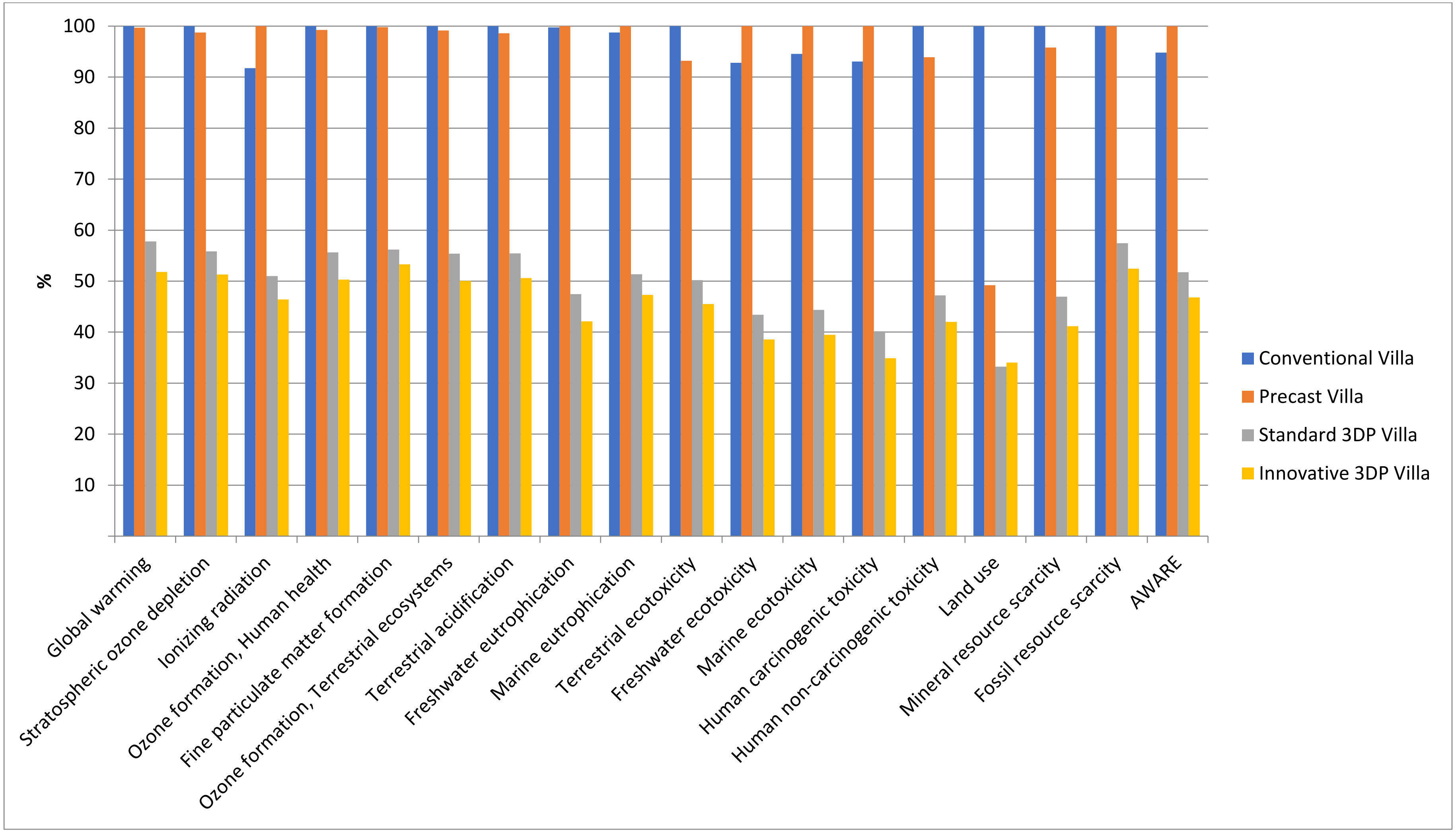
- **18 factors for 3tandard 3D Printed Villa**



- **18 factors for Innovative 3D Printed Villa**



- **Comparing All Villas**



- **Characterised Results for Conventional Villa**

Label	Unit	paint	Bitumen adhesive compound	Bitumen seal	Ceramic tile	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Cement mortar	Concrete block	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Electricity
Global warming	kg CO_2 eq	0.2088	0.321	0.6229	1.489	0.5902	0.4291	0.0242	0.7168	5.3486	0.178	0.8702	1.6606	43.405	0.1068	1.6188	0.3593	41.353	0.6975
Stratospheric ozone depletion	kg CFC11 eq	1.0562	2.6257	1.7362	3.2602	1.3895	0.9065	0.0862	1.2847	4.913	0.1669	4.0383	2.7175	27.3966	0.0013	0.6696	0.5124	44.825	2.4142
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.2589	0.5982	0.6856	11.7324	0.8883	0.6132	0.051	0.941	3.5689	0.1208	2.0425	1.6734	22.8223	0.0601	1.1357	0.1767	51.5976	1.0332
Marine eutrophication	kg N eq	3.0457	0.2875	0.6389	2.0264	1.5462	0.5957	0.2599	2.1479	4.0211	0.2139	1.8075	0.6896	25.2682	0.008	1.0056	0.3717	55.9755	0.0908
Land use	m2a crop eq	1.926	0.079	0.4097	1.2703	11.199	0.1695	0.2975	0.3632	4.1884	0.1874	56.34	1.492	9.8509	0.0003	0.2202	0.0155	11.9667	0.0246

Mineral resource scarcity	kg Cu eq	0.4173	0.0331	0.1486	1.8468	0.219	0.1169	0.0783	0.3864	1.1479	0.0575	0.1508	0.1664	12.1116	0.0007	0.023	0.0089	83.0753	0.0114
AWARE	m3 eq	0.2694	0.4072	1.2938	1.1088	0.5302	0.524	0.9949	0.5599	4.288	0.186	3.6407	0.5199	34.2932	0.0786	2.967	3.8685	44.2598	0.21

- **Normalised and Weighted Results for Conventional Villa**

Label	Unit	Paint	Bitumen adhesive compound	Bitumen seal	Ceramic tiles	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Cement mortar	Concrete block	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Electricity
Global warming	kg CO_2 eq	0.000597103	0.000918075	0.00178132	0.004258101	0.001687582	0.00122708	6.92812E-05	0.002049667	0.015294609	0.000509077	0.002488276	0.00474857	0.12411843	0.000305262	0.004629024	0.001027335	0.11825031	0.001994506
Stratospheric ozone depletion	kg CFC11 eq	304.6587734	757.4163285	500.8353464	940.4394874	400.8066299	261.4903391	24.85802189	370.5738493	1417.213236	48.15297251	1164.892998	783.8968852	7902.85192	0.384327328	193.1588847	147.8094575	12930.31054	696.4038463

Label	Unit	Paint	Bitumen adhesive compound	Bitumen seal	Ceramic tiles	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Cement mortar	Concrete block	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Electricity
Fine particulate matter formation	kg PM2.5 eq	3877.159133	8959.27259	10268.30408	175709.0062	13303.55214	9183.920742	764.6610128	14093.50617	53449.41521	1809.73022	30588.84775	25061.71145	341797.6843	900.3429022	17009.0181	2646.793772	772749.229	15473.05713
Marine eutrophication	kg N eq	0.335775124	0.031701002	0.070442524	0.223402019	0.170465955	0.065670756	0.028648191	0.236798748	0.443318093	0.023583509	0.199276508	0.076025426	2.785752146	0.000879002	0.110860327	0.040982866	6.171145673	0.010007114
Land use	m2a crop eq	1.21935E-05	5.0017E-07	2.59351E-06	8.04218E-06	7.08987E-05	1.07296E-06	1.88311E-06	2.29948E-06	2.65162E-05	1.1862E-06	0.000356679	9.44575E-06	6.23641E-05	1.92647E-09	1.39376E-06	9.82484E-08	7.5759E-05	1.55444E-07
Mineral reso	kg Cu	58.23087	4.623739	20.74390	257.71	30.56980	16.31214	10.92892	53.92186	160.1928	8.020230	21.05024	23.22397	1690.187	0.101986	3.206411	1.240578	11593.23	1.585015

Label	Unit	Paint	Bitumen adhesive compound	Bitumen seal	Ceramic tiles	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Cement mortar	Concrete block	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Electricity
urce scarcity	eq	442	841	001	8381	912	757	831	342	321	471	194	386	823	364	745	782	625	845
AWARE	m3 eq	0.000211513	0.000319779	0.001015944	0.000870619	0.0004163	0.000411505	0.00078121	0.000439646	0.003366979	0.000146117	0.002858737	0.000408222	0.026927603	6.1738E-05	0.00232977	0.003037649	0.034753528	0.000164881
		4240.385376	9721.345598	10789.95657	176907.3926	13735.10121	9461.79054	800.4774635	14518.24117	55027.28328	1865.927663	31774.99597	25868.91351	351393.6609	900.8304619	17205.50121	2795.888856	797279.1	16171.05816
		0%	1%	1%	11%	1%	1%	0%	1%	4%	0%	2%	2%	23%	0%	1%	0%	52%	1%

- **Characterised Results for Precast Villa**

Label	Unit	Paint	Bitumen adhesive compound, hot {RoW}| production | APOS, U	Bitumen seal	Ceramic tile	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Steel sheet	Electricity
Global warming	kg CO2 eq	0.209447008	0.322034821	0.624837017	1.344674823	0.591956449	0.430425125	0.024301897	0.718965538	0.123167618	1.799864882	47.56169927	0.107077225	1.179533548	0.360360381	36.27828848	7.537189203	0.786176719
Stratospheric ozone depletion	kg CFC11 eq	1.069676656	2.659337705	1.758465302	2.520869876	1.407257999	0.918109487	0.087278123	1.301108751	0.577162346	2.974062392	30.31230633	0.001349398	0.492662599	0.518968562	39.70703921	10.94670335	2.747641914
Fine particulate	kg PM2.	0.259434188	0.599496054	0.687087902	11.77298617	0.890186893	0.614528042	0.051166125	0.943045462	0.288835004	1.812076851	24.9849799	0.060245072	0.826777976	0.177106166	45.22430281	9.644289679	1.1634557

Label	Unit	Paint	Bitumen adhesive compound, hot {RoW}| production | APOS, U	Bitumen seal	Ceramic tile	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Steel sheet	Electricity
matter formation	5 eq																	
Marine eutrophication	kg N eq	3.007342155	0.283927401	0.630912649	2.886118748	1.526764238	0.5881747	0.256585156	2.120868423	0.251862525	0.735775783	27.25668939	0.007872705	0.721284427	0.367059652	48.34146872	10.9165762	0.100717127
Land use	m2a crop eq	3.91334751	0.160523162	0.832352862	2.764542533	22.75403268	0.344353239	0.604358632	0.737988994	16.15362767	3.275735803	21.86506057	0.000618275	0.324939681	0.03153157	21.26541755	4.91550905	0.056060206

Label	Unit	Paint	Bitumen adhesive compound, hot {RoW}| production | APOS, U	Bitumen seal	Ceramic tile	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Steel sheet	Electricity
Mineral resource scarcity	kg Cu eq	0.435598402	0.034588072	0.15517558	1.932378833	0.228678689	0.122023677	0.081754289	0.403364671	0.022220979	0.187724866	13.81224407	0.000762913	0.017424019	0.0092802	75.8503123	6.693144685	0.013323757
AWARE	m3 eq	0.255456709	0.386215001	1.227012988	1.078959822	0.502788807	0.4969972	0.943510853	0.530984718	0.487221794	0.532755383	35.52821056	0.074564516	2.044035647	3.668739661	36.71114633	15.30762542	0.223774593

- **Normalised and Weighted Results for Precast Villa**

Label	Unit	paint	Bitumen adhesive compound	Bitumen seal	Ceramic tile	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Electricity	Steel sheet
Global warming	kg CO_2 eq	0.000598921	0.00092087	0.001786744	0.003845146	0.001692721	0.001230816	6.94922E-05	0.002055908	0.000352202	0.005146779	0.136004395	0.000306191	0.003372919	0.001030464	0.103739075	0.002248101	0.021552864
Stratospheric ozone depletion	kg CFC11 eq	308.5605738	767.1166457	507.2496063	727.1740027	405.9398074	264.8392752	25.1763816	375.3198321	166.4891384	857.9026132	8743.934519	0.389249452	142.1142114	149.7024698	11453.95362	792.5890135	3157.70289
Fine particulate matter formation	kg PM2.5 eq	3885.403688	8978.323948	10290.13907	176317.5637	13331.84138	9203.449795	766.2870229	14123.47521	4325.723605	27138.4822	374186.3552	902.2574304	12382.20077	2652.422015	677299.6057	17424.43859	144437.2426

Label	Unit	paint	Bitumen adhesive compound	Bitumen seal	Ceramic tile	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Electricity	Steel sheet
Marine eutrophication	kg N eq	0.331551503	0.031302244	0.069556448	0.318186943	0.168321711	0.064844702	0.028287833	0.233820123	0.027767176	0.08111733	3.00497777	0.000867945	0.079519697	0.040467354	5.329518813	0.011103796	1.203523595
Land use	m2a crop eq	2.47747E-05	1.01624E-06	5.26948E-06	1.75018E-05	0.000144052	2.18004E-06	3.82609E-06	4.67208E-06	0.000102266	2.07381E-05	0.000138424	3.91419E-09	2.05714E-06	1.99621E-07	0.000134628	3.54907E-07	3.11192E-05
Mineral resource scarcity	kg Cu eq	60.78817081	4.826798296	21.65489956	269.6653017	31.91232825	17.02851999	11.40888862	56.28992305	3.100958691	26.19718342	1927.511781	0.106465249	2.431538388	1.295060659	10584.98313	1.859342996	934.0346987
AWARE	m3 eq	0.000200589	0.000303263	0.000963472	0.000847218	0.000394799	0.000390251	0.000740861	0.000416938	0.000382575	0.000418329	0.027897369	5.85494E-05	0.001605012	0.002880758	0.028826231	0.000175712	0.012019814
		4255.08	9750.29	10819.1	177314.	13769.8	9485.38	802.901	14555.3	4495.34	28022.6687	384860.	902.754	12526.8	2803.46	699344.	18218.9	148530.

Label	Unit	paint	Bitumen adhesive compound	Bitumen seal	Ceramic tile	Doors	Double glazing windows	Gypsum fibreboard	Window frame, aluminium	Plywood	Transportation	Concrete mix	Polyethylene	Polystyrene	Polyvinylchloride	Reinforcing steel	Electricity	Steel sheet
		480 8	991 9	158 9	725 9	640 7	405 8	395 1	212 6	230 6		970 5	377 8	310 2	392 4	004 7	004 7	217 3
		0%	1%	1%	12%	1%	1%	0%	1%	0%	2%	25%	0%	1%	0%	45%	1%	10%

- **Characterised Results for Standard 3D Printed Villa**

Label	Unit	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for robot	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production, oil
Global warming	kg CO2 eq	16.0784	0.0028	0	0.5647	0.03	0.1855	0.0035	0.971	29.6595	40.7724	1.1794	0.706	2.4465	0.0399	1.2438	0.1836	1.0233	0.4029	0.3422	0.5912	0.1547	1.8672	0.8625	0.689
Stratospheric ozone depletion	kg CFC11 eq	7.9462	0.0066	0	0.9207	0.0688	0.4989	0.006	2.3673	33.2888	26.6466	2.1887	1.5444	5.5462	0.1468	0.5327	0.0024	2.953	3.7574	1.7921	0.873	0.7432	3.1638	2.5372	2.4692
Fine particulate matter formation	kg PM2.5 eq	7.1201	0.0049	0	0.5244	0.0282	0.2595	0.0037	1.5036	38.0683	22.0527	1.5928	1.038	19.8286	0.0864	0.8976	0.1063	1.1585	0.6509	0.4364	0.2991	0.3734	1.9355	0.9812	1.0498
Marine eutrophication	kg N eq	5.7926	0.0054	0	0.968	0.054	0.103	0.0016	2.8295	44.6497	26.3975	3.9306	1.09	3.7026	0.4754	0.8593	0.0152	1.1673	0.2827	5.5509	0.6803	0.3573	0.8623	0.1248	0.0997
Land use	m2a crop eq	2.4062	0.0012	0	0.3116	0.0764	0.4831	0.0055	32.0652	14.9349	16.1017	1.04	0.4853	3.6317	0.8515	0.2943	0.0009	1.1709	0.1708	5.4924	0.0444	17.4242	2.9193	0.0462	0.0422
Mineral resource scarcity	kg Cu eq	5.5555	0.0002	0	0.127	0.012	0.0468	0.0004	0.4438	73.3578	14.007	0.7828	0.2368	3.7356	0.1586	0.0217	0.0015	0.3006	0.0577	0.8419	0.018	0.033	0.2304	0.0169	0.0138
AWARE	m3 eq	3.1947	0.9266	0	0.8488	0.0177	6.9296	0.0012	0.924	33.6215	34.118	0.9758	0.9133	1.9294	1.7335	2.4145	0.1432	2.251	0.0502	0.4675	6.7419	0.6853	0.6191	0.2737	0.2197

- **Normalised and Weighted Results for Standard 3D Printed Villa**

Label	Unit	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for robot	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity	Electricity electricity production, oil
Global warming	kg CO2 eq	0.045976689	8.07705E-06	0	0.001614855	8.56696E-05	0.000530437	1.0142E-05	0.00277682	0.084812475	0.116590157	0.00337261	0.00201909	0.006995939	0.006995939	0.003556645	0.000524907	0.002926029	0.001151977	0.000978519	0.001690422	0.000442243	0.005339321	0.002466431	0.00197018
Stratospheric ozone depletion	kg CFC11 eq	2292.181201	1.900640398	0	265.5907354	19.83454028	143.9158043	1.733553132	682.8687824	9602.535914	7686.506372	631.3600983	445.5105684	1599.854222	1599.854222	153.6686676	0.684275197	851.8265381	1083.862527	516.9556254	251.8283297	214.3720662	912.6446371	731.8955052	712.281086

Label	Unit	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for robot	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity	Electricity electricity production, oil
Fine particulate matter formation	kg PM2.5 eq	106634.044	72.95415945	0	7854.018499	421.9514784	3886.14402	55.06125808	22517.86263	570128.502	330271.7675	23854.95485	15544.89085	296961.9216	296961.9216	13443.33641	1592.555825	17350.50434	9747.945666	6535.975094	4480.016906	5592.454556	28987.4945	14694.28994	15722.5711
Marine eutrophication	kg N eq	0.638620584	0.000589933	0	0.106730369	0.005947904	0.011354856	0.000180585	0.311949338	4.922512575	2.910259209	0.433337043	0.12017619	0.408207235	0.408207235	0.094730721	0.001680983	0.128687142	0.031168665	0.611972839	0.074997837	0.039389667	0.095070478	0.013763106	0.010993682

Label	Unit	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for robot	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity	Electricity electricity production, oil
Land use	m2a crop eq	1.52333E-05	7.37586E-09	0	1.97295E-06	4.83756E-07	3.0586E-06	3.51049E-08	0.000202999	9.45506E-05	0.000101937	6.58393E-06	3.07213E-06	2.2992E-05	2.2992E-05	1.86342E-06	5.76427E-09	7.41305E-06	1.08135E-06	3.47713E-05	2.81307E-07	0.000110309	1.84813E-05	2.92335E-07	2.67189E-07
Mineral resource scarcity	kg Cu eq	775.2819175	0.034760711	0	17.73310576	1.680894049	6.524724335	0.061067749	61.928741	10237.14449	1954.687243	109.2356545	33.04537365	521.305264	521.305264	3.033102517	0.215908035	41.95114012	8.047662466	117.4870634	2.513181609	4.606132337	32.14966547	2.365195132	1.927618212
AWARE	m3 eq	0.00250	0.00072	0	0.00066	1.39139	0.00544	9.23432	0.00072	0.02640	0.02679	0.00076	0.00071	0.00151	0.00151	0.00189	0.00011	0.00176	3.9421E	0.00036	0.00529	0.00053	0.00048	0.00021	0.00017

Label	Unit	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for robot	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity	Electricity electricity production, oil
		855	7595		649	E-05	1233	E-07	5503	0155	0045	6189	7146	4985	4985	5895	2438	7489	-05	712	3836	813	6149	4886	2501
		109702.19442	74.89088618	0	8137.4513554	443.4729607	4036.601878	56.85607064	23262.97558	589973.2162	339916.0149	24595.98808	16023.56971	299083.4979	299083.4979	13600.13837	1593.458327	18244.4154	10839.88822	7171.031137	4734.4404	5811.473235	29932.38972	15428.56709	16436.79294
		6%	0%	0%	0%	0%	0%	0%	1%	32%	18%	1%	1%	16%	16%	1%	0%	1%	1%	0%	0%	0%	2%	1%	1%

- **Characterised Results for Innovative 3D Printed Villa**

Label	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel (footing)	Concrete mix	Window frame, aluminium	Double glazing window	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
Global warming	13.91879881	0.002445212	0	0.488875596	0.025934657	0.160582464	0.014126774	1.377459952	28.15984285	42.15273424	1.735581202	1.288877447	3.175233586	0.037137409	1.422622251	0.189856421	0.994862323	0.414608333	0.344383783	0.660071587	0.150403963	1.932032137	0.790415537	0.563113463
Stratospheric ozone depletion	6.707746772	0.005561954	0	0.777215439	0.058041655	0.421149387	0.023341153	3.274402649	30.8191086	26.86312301	3.140650387	2.749018217	7.01897573	0.133366258	0.594152634	0.00239242	2.799620505	3.770787599	1.758693596	0.950526399	0.704741526	3.192226147	2.267249031	1.967908932

Label	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel (footing)	Concrete mix	Window frame, aluminium	Double glazing window	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
Fine particulate matter formation	5.823445421	0.003984134	0	0.428920531	0.023042871	0.212228152	0.013835272	2.015015571	34.14784514	21.54048003	2.21450915	1.790043979	24.31366962	0.076060986	0.97000994	0.103910083	1.064183498	0.632888764	0.414957599	0.31556997	0.343099867	1.892165157	0.849483929	0.81065034
Marine eutrophication	4.872070981	0.004500627	0	0.814253231	0.045375831	0.086626809	0.006338832	3.899616265	41.18735934	26.51564298	5.619675775	1.933218847	4.668926194	0.430391447	0.954875004	0.015321908	1.102620689	0.282695601	5.427652632	0.737991433	0.33758797	0.866923153	0.11150027	0.079184418

Label	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel (footing)	Concrete mix	Window frame, aluminium	Double glazing window	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
Land use	1.821368684	0.000881893	0	0.235895974	0.057838923	0.365701143	0.019312076	39.77082422	12.39864829	14.5557994	1.338146736	0.774524521	4.121408842	0.693718306	0.294373722	0.00082343	0.995452863	0.153709529	4.83319077	0.0433827	14.81664238	2.641193987	0.037000493	0.030161116
Mineral resource scarcity	4.914805008	0.000220361	0	0.112417061	0.010655576	0.04136269	0.001781214	0.643288814	71.17572362	14.79870499	1.177133726	0.441722172	4.954551694	0.151033421	0.025404972	0.001635288	0.298683129	0.060652198	0.865856437	0.020549554	0.03280326	0.243605634	0.01587216	0.011537017
AWARE	2.7400	0.7947	0	0.7279	0.0151	5.9432	0.0046	1.2984	31.625	34.946	1.4225	1.6516	2.4808	1.6002	2.7360	0.1467	2.1682	0.0511	0.4661	7.4581	0.6603	0.6346	0.2484	0.1778

Label	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel (footing)	Concrete mix	Window frame, aluminium	Double glazing window	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
	13384	29811		87829	97345	9349	40794	82759	88912	45145	91621	9294	68232	20009	82109	30956	37016	90238	73094	69624	14457	92914	62312	88498

- **Normalised and Weighted Results for Standard 3D Printed Villa**

Label	Cement and fly ash	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
Global warming	13.91879881	0.039801307	6.9217E-06	0	0.001397957	7.4161E-05	0.000459191	4.0396E-05	0.003938896	0.080524087	0.120537265	0.004962957	0.003685592	0.009079695	0.000106196	0.00406804	0.000542901	0.002844845	0.001185587	0.000984778	0.001887499	0.000430086	0.005524716	0.002260222	0.001610243
Stratospheric ozone depletion	6.707746772	1934.926954	1.604409873	0	224.1967614	16.74278511	121.4854001	6.733024933	944.5392257	8890.127481	7748.977791	905.9568425	792.9860241	2024.704537	38.47103585	171.3901827	0.690121131	807.5828381	1087.727192	507.3154604	274.1903074	203.2908247	920.8344655	654.0141435	567.666038

Label	Cement and fly ash	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
pletion																									
Fine particulate matter formation	5.823445421	87214.55151	59.66819113	0	6423.707798	345.1004468	3178.424759	207.2032868	30177.78421	511413.5678	322599.9677	33165.49025	26808.50795	364132.5089	1139.123712	14527.30743	1556.204389	15937.6932	9478.428274	6214.592619	4726.118543	5138.418727	28337.92088	12722.25539	12140.66601
Marine eutrop	4.872070	0.537132	0.000496	0	0.089769	0.005002	0.009550	0.000698	0.429922	4.540797	2.923279	0.619554	0.213132	0.514736	0.047449	0.105272	0.00168	0.121561	0.031166	0.598384	0.08136	0.037218	0.095575	0.012253	0.008729

Label	Cement and fly ash	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
hication	981	914	182		261	565	376	839	359	214	368	361	255	739	516	439	92	009	441	318	16	179	98	996	872
Land use	1.821368684	1.15308E-05	5.58311E-09	0	1.49342E-06	3.66168E-07	2.31519E-06	1.22261E-07	0.000251782	7.84937E-05	9.21502E-05	8.47158E-06	4.90338E-06	2.60919E-05	4.39181E-06	1.86363E-06	5.21299E-09	6.30204E-06	9.73108E-07	3.05981E-05	2.74648E-07	9.38016E-05	1.67209E-05	2.34244E-07	1.90945E-07
Mineral resource scarcity	4.91480508	685.8657075	0.030751608	0	15.68790765	1.486995692	5.7722027	0.24857004	89.77156505	9932.639842	2065.173339	164.2701297	61.64274867	691.4123953	21.0768574	3.545287929	0.228206041	41.68151442	8.464071889	120.8310883	2.8677975	4.577726076	33.99539757	2.214975074	1.610001673

Label	Cement and fly ash	Cement and fly ash	Tap water	Silica fume	Polycarboxylates	Fibre	Sand gravel and quarry	Transportation for gantry	Doors	Reinforcing steel	Concrete mix	Window frame, aluminium	Double glazing windows	Ceramic tile	Gypsum fibreboard	Polystyrene	Polyethylene	Bitumen seal	Bitumen adhesive compound	Paint	Polyvinylchloride	Plywood	Transportation	Electricity production mix	Electricity electricity production oil
AWARE	2.740013384	0.002151506	0.000624036	0	0.000571629	1.19332E-05	0.004666777	3.64403E-06	0.001019591	0.024833198	0.027440561	0.001117044	0.001296938	0.001948021	0.001256521	0.002148419	0.000115216	0.001702537	4.01955E-05	0.000366047	0.005856284	0.00051849	0.000498372	0.000195097	0.000139681
		89835.92327	61.30447982	0	6663.684207	363.3353166	3305.69704	214.1856247	31212.53014	530240.9813	332417.1902	34236.34287	27663.35484	366849.1516	1198.720422	14702.35439	1557.125063	16787.08367	10574.65193	6843.338933	5003.265666	5346.325539	29292.85236	13378.49922	12709.95253
		6%	0%	0%	0%	0%	0%	0%	2%	34%	22%	2%	2%	24%	0%	1%	0%	1%	1%	0%	0%	0%	2%	1%	1%

- **Characterised Results All Villas**

Label		charachterised data Conventional Villa	Precast Villa	Standard 3DP Villa	Innovative 3DP Villa
Global warming	kg CO2 eq	100	99.6964	57.8103	51.7743
			0.3%	73%	48%
Stratospheric ozone depletion	kg CFC11 eq	100	98.7355	55.8323	51.2789
			1%	44%	49%
Fine particulate matter formation	kg PM2.5 eq	100	99.7878	56.199	53.2726
			0.2%	44%	47%
Marine eutrophication	kg N eq	98.7421	100	51.3268	47.3122
			-1.3%	48%	52%
Land use	m2a crop eq	100	49.2175	33.2225	34.028
			51%	67%	66%
Mineral resource scarcity	kg Cu eq	100	95.7931	46.9557	41.1507
			4%	53%	59%
AWARE	m3 eq	94.8351	100	51.7636	46.7921
			-5%	45%	51%

- **Normalised Results for All Villas**

Normal. Factor	Normalized			
	Conventional Villa	**Precast Villa**	**Standard 3DP Villa**	**Innovative 3DP Villa**
8095.53	0.012352503	0.012315006	0.007141023	0.006395417
0.053647991	1864.002714	1840.432095	1040.71651	955.8394052
0.000595387	167958.0014	167601.6072	94390.74527	89475.56661
19.54518155	5.051993339	5.11635053	2.626059865	2.420660504
819498.1829	0.000122026	6.00581E-05	4.05401E-05	4.1523E-05
0.063640278	1571.331911	1505.227591	737.8306174	646.6143716
11468.70864	0.008269033	0.008719377	0.004513464	0.004079983

- **Weighted Results for All Villas**

Weighted			
Conventional Villa	**Precast Villa**	**Standard 3DP Villa**	**Innovative 3DP Villa**
0.274102048	0.273269977	0.158459296	0.141914309
	0.30%	42.19%	48.23%
12582.01832	12422.91664	7024.836441	6451.915985
	1.26%	44.2%	48.72%
1602319.333	1598919.333	900487.7099	853596.9054
	0.21%	43.8%	46.7%
15.76221922	15.96301365	8.193306778	7.552460772
	-1.27%	48.0%	52.1%
0.001027458	0.000505689	0.000341348	0.000349624
	50.78%	66.8%	65.97%
12696.36184	12162.23894	5961.671389	5224.644123
	4.4%	53.0%	58.85%
0.074669367	0.078735979	0.040756584	0.036842249
	-5.45%	45.4%	50.66%
1627613.825	**1623520.804**	**913482.6106**	**865281.1971**
	0.25%	43.9%	46.84%

Appendix D

- **Cost of Materials for All Villas (SAR)**

Conventional Villa	Unit	Quantity	(Average) Unit price (SAR)	Sub-Quantity	Amount per unit (SAR)	Total Amount (SAR)
Concrete mix	m3	25.63	203		5202.89	**50884.17**
steel bars	Ton	3.36	2,536.64		8523.11	
Concrete masonry units (CMU) for outside Walls	Pcs	3.876	1,531.16	1531.16 SAR for 1000 pc	5934.78	
Concrete masonry units (CMU) for inside walls	Pcs	3.096	3,600.00	3600 SAR for 1000 pc	11145.6	
Mortar for Concrete masonry units (CMU)						
Cement	Bag	83	14.13		1172.79	
Sand	m3	6.9	24.08		166.15	
Mortar foe walls						
Cement	bag	428	14.13		6047.64	
Sand	m3	517.7	24.08		12466.22	
Water	Ton	30	7.5		225	
Concrete mix	m3	317.75	203		64503.25	**95259.96**
steel bars	Ton	11.04	2,536.64		28004.51	
Polystyrene (EPS) inside masonry	m2	366.96	7.5		2752.2	
Cement	Bag	609.15	14.13		8607.34	**23454.35**
Fly-ash	Ton	8.65	395		3416.74	
Silicafume	Ton	4.39	805		3530.66	
Sand/ aggregates	m3	42.62	42.01		1790.47	
Water	Ton	12.18	18 ton 119		119	
Polycarboxylate ether superplasticiser (SP)	kg	852.82	5		4264.08	
Fibre	Kg	60.92	28.33	1725.732574	1726.07	
Cement	Bag	472.275	14.13		6673.25	**21153.51**
Fly-ash	Ton	6.71	395		2648.99	

Conventional Villa	Unit	Quantity	(Average) Unit price (SAR)	Sub-Quantity	Amount per unit (SAR)	Total Amount (SAR)
Silicafume	Ton	3.40	805		2737.3059	
Sand/ aggregates	m3	33.05	42.01		1388.43	
Water	Ton	9.45	18 ton 119		119	
Polycarboxylate ether superplasticiser (SP)	kg	661.19	5		3305.93	
Fibre	Kg	47.23	28.333	1338.096758	1338.11	
steel ties	Ton	1.16	2,536.64		2942.5024	

- **Cost of Construction for All Villas (SAR)**

Conventional Villa	Unit	Quantity	Number of days for each labour	Total of days	Hours for the job to be completed	(Average) salaries per month (SAR)	(Average) Unit price (SAR)	Amount per unit (SAR)
Electricity production, oil (Diesel)	Kwh	54.75					0.52 SAR/liter	28.47
Formwork material (Plywood)	m3	1.6					20	31.74
labour								
Structural Engineer	Hourly rate of pay	1	4	4	32	15,983	76.84	2458.92
Carpenter & Carpenter's assistant	Hourly rate of pay	8	6	48	384	1,712	8.23	3160.62
Blacksmith & Blacksmith's assistant	Hourly rate of pay	9	5	45	360	1,712	8.23	2963.08

Conventional Villa	Unit	Quantity	Number of days for each labour	Total of days	Hours for the job to be completed	(Average) salaries per month (SAR)	(Average) Unit price (SAR)	Amount per unit (SAR)
Site labours	Hourly rate of pay	2	16	32	256	1,712	8.23	2107.08
Workers supervisor	Hourly rate of pay	1	16	16	128	1,712	8.23	1053.54
Builder & Builder's assistant	Hourly rate of pay	8	8	64	512	1,712	8.23	4214.15
Total		29		209	1672			16017.60
Electricity production, oil (Diesel)	Kwh	555.4					0.52 SAR/liter	288.808
Formwork material (Steel Sheets)	Ton	51.86					150	7779
Labour								
Structural Engineer	Hourly rate of pay	1	3	3	24	15,983	76.84	1844.19
Surveyor Engineer	Hourly rate of pay	1	3	3	24	15,983	76.84	1844.19
Structural Engineer (Designer)	Hourly rate of pay	1	2	2	16	15,983	76.84	1229.46
Preparing casting mould	Hourly rate of pay	4	4	16	128	1,712	8.23	1053.54

Conventional Villa	Unit	Quantity	Number of days for each labour	Total of days	Hours for the job to be completed	(Average) salaries per month (SAR)	(Average) Unit price (SAR)	Amount per unit (SAR)
Preparing formation for reinforced steel	Hourly rate of pay	8	6	48	384	1,712	8.23	3160.62
Pouring concrete in formwork	Hourly rate of pay	6	2	12	96	1,712	8.23	790.15
Loading parts from factory to site	Hourly rate of pay	5	1	5	40	1,712	8.23	329.23
Trucks and crane drivers	Hourly rate of pay	7	5	35	280	2,351	11.30	3164.81
Installation on site	Hourly rate of pay	8	3	24	192	1,712	8.23	1580.31
Total		41		148	1184			23064.31
Electricity production, grid	Kwh	1521.14					18 halalah/Kwh	273.81
labour								
Engineer	Hourly rate of pay	1	7	7	56	15,983	76.84	4303.12
Printer operator	Hourly rate of pay	1	7	7	56	8,720	41.92	2347.69
Site labours	Hourly rate of pay	6	7	42	336	1,712	8.23	2765.54

Conventional Villa	Unit	Quantity	Number of days for each labour	Total of days	Hours for the job to be completed	(Average) salaries per month (SAR)	(Average) Unit price (SAR)	Amount per unit (SAR)
Total					448			9690.15
Electricity production, grid	Kwh	1248.45					18 halalah/Kwh	224.721
labour								
Engineer	Hourly rate of pay	1	6	6	48	15,983	76.84	3688.38
Printer operator	Hourly rate of pay	1	6	6	48	8,720	41.92	2012.31
Site labours	Hourly rate of pay	6	6	36	288	1,712	8.23	2370.46
Total					384			**8295.87**