FINANCIAL AND ENVIRONMENTAL SUSTAINABILITY OF 3D PRINTED CONCRETE WALLS IN SRI LANKA

MASTER OF SCIENCE

IN

CONSTRUCTION PROJECT MANAGEMENT

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November 2022

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This report was submitted to the Department of Civil Engineering of the University of Moratuwa in partial fulfilment of the requirements for the Master of Science in Construction Project Management.

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November 2022

DECLARATION

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ABSTRACT

At present, increased housing cost associated with complex human expectations, have deprived the people from affording a dwelling which is one of the basic human needs. This urges the use of sustainable solutions in housing construction. With the remarkable entrance of 3D printing technology to the construction industry, it is worthwhile to focus on sustainability aspects of this new technology in the Sri Lankan housing sector. In the view of that, this research is aimed at assessing the sustainability of 3D printed concrete walls compared to the other walling types used and which have potential to be used in the housing construction in Sri Lanka.

Since 3D printing has not been used in the Sri Lankan construction sector, 'secondary data analysis' was selected as the research methodology with the use of previous researches, 3D printer vendors and printer manuals. Technical aspects required for the study such as printing mechanism, printing material etc. was selected based on the knowledge gained through literature survey. Life Cycle Cost and Embodied Energy of 3D printed concrete walls were calculated in order to ascertain the economic and environmental sustainability, based on the same case studies followed by the previous researches on different walling materials and the results were compared against such previous research results.

With related to economic sustainability, the research findings identified that 3D printed concrete walls has the second lowest Life Cycle cost with low maintenance cost and energy cost which offset the high initial cost and low resale value. In terms of environmental sustainability, 3D printed concrete walls possess a middle rank as per the Embodied Energy calculation results.

In combination, 3D printed concrete walls are both economically and environmentally sustainable compared to the Brick and Cement Block walls which are the two dominant walling types in the Sri Lankan housing sector. Therefore, 3D printing prooves a great potential to be used in Sri Lanka, when its sustainability performance are bundled together with other advantages such as ability to be printed in complex shapes with no additional cost enabling advanced architectural features, less labour intensiveness and less time consumption. In addition, the results of this research provides clear guidance on the level of economic and environmental sustainbility achievable through 3D printed concrete walls in comparison with other potential walling types in Sri Lankan housing sector.

Thus, this research provides inputs to the contractors, investors, and developers in Sri Lanka, on the sustainability dimensions of 3D printed walls against other walling types in order to seek improvements to their construction practices and efficiencies.

Key Words: Economic Sustainability, Environmental Sustainability, Life Cycle Cost, Embodied Energy, 3D printed concrete walls

ACKNOLEDGEMENT

I would like to express my gratitude to my dissertation supervisor Prof. R. U. Halwatura for all the guidance, assistance and continuous encouragement provided to me.

I wish to deliver my gratefulness towards the head of the Department of Civil Engineering Prof. (Mrs.) C. Jayasinghe and the Course Coordinator of M.Sc. in Construction Project Management Dr. Chandana Siriwardana for the valuable guidance, encouragement and assistance provided.

I should deliver my gratefulness to all the lecturers for their guidance and assistance. Their direction throughout the process and clear knowledge on the subject are very much appreciated.

I should express my appreciation to programme assistance and other non-academic staff members in the Department of Civil Engineering for their support.

It is also my duty to acknowledge to my batchmates, and especially for my family members, for their support and assistance.

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CHAPTER 01 INTODUCTION

1.1 Background

‘Shelter’ is one of the basic human needs that ensure the minimum standard of living (ILO, 2022). With socio-economic development and increased complexity of human expectations, people tend build shelters with better protection, privacy, comfort and architecture. Subsequently, availability and quality of housing has become an indicator of people’s living standard, socio-economic development, community growth and stability of a nation, improved health conditions, increased safety and education (Assaf, et al., 2010)

Simultaneous to the increased requirements attached to housing need, housing cost has gradually become the single largest expenditure that the households and families spend (Assaf, et al., 2010). According to Trading Economics (2019), housing cost indicate an upward trend leaving less for other household expenditure. Further, in Sri Lankan context, the real estate prices in Colombo have increased as a result of the high demand created due to the migration to Colombo area (Ministry of Housing, Construction & Culture Affairs, 2017). Accordingly, the increased housing cost has deprived the ability of people to acquire a house (Ministry of Housing, Construction & Culture Affairs, 2017). This situation is confirmed by Lanka Business News (2018) stating that the demand for houses has been shifted from “luxury housing” to “affordable housing” in Sri Lanka especially in Colombo and its suburbs since people cannot afford to buy “luxury” houses. Thus, it is worthwhile to look into the factors contributing to increase the housing cost.

Among several external factors like high demand, increased lending rates, taxation, confidence in investment market, environmental factors, financing factors and the high construction cost is leading in determining the increased housing cost. (Assaf, et al., 2010) (Ministry of Housing, Construction & Culture Affairs, 2017). Further, according to Assaf, et al. (2010), cost of materials, cost of labour and inadequte labour force, duration, lack of productivty as main construction related cost factors in housing sector. In Sri lankan context, while Ministry of Housing, Construction & Culture

Affairs (2017) presented labour shortage as the major factor affecting high construction cost in housing sector, Colombo Page (2018) identifies scarcity of skilled labour as the main reason. This urges the requirement of finding cost effective methods in housing construction, to create affordability in housing sector (Imitiaz, 2017).

In response to this scenario, the housing construction sector worldwide has stepped forward to introduce modern technologies among which 3D printing is prominent (Tay, et al., 2017). 3D printing which is applied to diverse fields, can be a good alternative that addresses housing problems and provide economical and dignified houses to people all over the world (Weinstein & Nawara, 2015). It involves an advanced manufacturing process that can create complex shape geometries automatically from a 3D computer-aided design model. The use of 3D printing in construction industry ranges from single story houses to large commercial buildings (Teizer, et al., 2018).

Using the 3D printing technology buildings can be built in any shape (Weinstein & Nawara, 2015) where, the cost of 3D printed concrete walls is not dependent on the shape of the walls unlike the conventional walls (Gao, et al., 2015), (Ngo, et al., 2018). This technology significantly reduced cost of construction (Bos, et al., 2016) (Hager, et al., 2016). Yingchuang which is a 3D printing company located in China stated that 3D printing can save 30 – 60% of materials used in construction (Chanrapaul, et al., 2017) (Sakin & Kiroglu, 2017). 3D printing reduces construction duration, labour involvement and wastage of material (Ngo, et al., 2018), (Sakin & Kiroglu, 2017). As per Yingchuang, 3D printing can reduce 50 – 70% of construction duration and 50 - 80% of labour involvement (Chanrapaul, et al., 2017). Walls can be reinforced with steel meshes or plastic fibres without reinforcement bars (Weinstein & Nawara, 2015), time consuming formwork is not required (Teizer, et al., 2018) (Weinstein & Nawara, 2015) and also construction waste is one of the materials that is used in 3D printed buildings reducing the cost of the construction (Yang, et al., 2018). Further, the method increase buildability, functional integrity, and accuracy of construction (Chanrapaul, et al., 2017) (Panda & J, 2018) and minimizes health and safety hazards (Bos, et al., 2016).

However, some researchers believed there is no or insignificant cost saving of the 3D printing technology over the conventional construction methods (Labonnote, et al., 2016) while highlighting some disadvantages. According to (Gao, et al., 2015), 3D printing technology is more suitable for low volume production of customized features which has complex geometry, printing high quality elements takes more build time as more layers are required and the material range that can be used for 3D printing is limited.

Accordingly, it is worthwhile to see whether 3D printing is a sustainable solution for the challenges faced by the housing construction sector in Sri Lanka. During the past few years, many researches have been published on different aspects of the building and construction using the 3D printed methodologies (Tay, et al., 2017). They have identified that 3D printing of Concrete as an emerging technology and it has ability to overcome many challenges faced by construction industry (Bos, et al., 2016). Although researches have been conducted in Sri Lanka to identify suitable walling materials for the country environmentally, socially and economically (Kandamby, 2011) (Udawatta & Halwatura, 2017) (Arooz & Halwatura, 2019), no research has been done to identify whether 3D printed concrete walls is a sustainable solution in the Sri Lankan context. Therefore, this study is focused on investigate whether 3D printing technology can be used to create a sustainable built environment in Sri Lankan housing sector.

1.2 Problem Statement

Although "shelter" is a basic human need (ILO, 2022) and nowadays an indicator of socio-economic development of a nation and its people (Assaf, et al., 2010), increased housing cost has deprived the people from a shelter (Ministry of Housing, Construction & Culture Affairs, 2017). Increased construction cost plays a key role in determining the affordability of houses (Ministry of Housing, Construction & Culture Affairs, 2017) which urge the involvement of emerging technologies to make the housing sector sustainable (Tay, et al., 2017). The industry worldwide identifies 3D printing as such leading technology with high potential to strengthen cost effectiveness and sustainability in the housing construction (Weinstein & Nawara, 2015).

Despite all these emphasis 3D printing is not a well-established technology in housing construction sector in Sri Lanka. In response to this situation, the research aims to identify the sustainability of 3D printed concrete walls compared to the other walling types used and having potential to be used in housing construction in Sri Lanka.

1.3 Aims and objectives

The aim of this research study is to explore whether concrete 3D printed wall is a sustainable walling material that can be widely used in Sri Lanka. In order to achieve the aim, the following objectives were addressed to,

1. Identify what are the methods, shapes, equipment, and materials that are frequently used for concrete 3D printing.
2. Calculate the indicators to ascertain the sustainability of 3D printed concrete walls.
3. Compare the sustainability measures of 3D printed concrete walls with other walling materials available in Sri Lanka.

1.4 Methodology

A comprehensive literature review was carried out by referring the published and unpublished literature on 3D printing in the construction background. It was basically carried out in order to identify the methods, shapes, equipment, and materials that are frequently used for concrete 3D printing (objective 1).

Objective 2 (calculate sustainability indicators of 3D printing) and objective 3 (Compare the sustainability indicators with other walling types) was carried out through secondary data analysis and subsequent comparisons.

1.5 Scope and Limitation

The research was conducted within the boundaries of Sri Lanka. In Sri Lankan Context, 3D printing has never been used for Construction. Hence, the analsysis is based on some assumptions and data obtained from literature and in selecting sustainability mesures, the available data on other projects was to be considered.

1.6 Main Findings

Economic sustainability measurement: 3D printed wall has the second lowest Life Cycle cost compared to the considered walling types with low maintenance cost and energy cost which offset the high initial cost and low resale value.

Environmental sustainability measurement: 3D printed concrete walls possess a middle rank as per the Embodied Energy calculation.

Economical and Environmental Sustainability of 3D printed concrete walls:

- Both economically and environmentally sustainable compared to Brick walls, Cement Block walls and Cement Stabilized Earth Block Walls;
- Economically sustainable but environmentally unsustainable compared to Cabook Block walls, Mud Concrete Block walls and Fly Ash Stabilized Earth Block walls;
- Both economically and environmentally unsustainable compared to Mud Concrete walls.

1.7 Chapter Breakdown

Chapter One: Introduction

This chapter includes the background to the research topic, research problem, aim and objectives, scope and limitations, methodology in brief and the organization of the report.

Chapter Two: Literature Review

This chapter reviews the existing literature to identify the methods, shapes, equipment, and materials that are frequently used for concrete 3D printing. This chapter mainly focused on fulfilling first objective.

Chapter Three: Research Methodology

This chapter describes the methodology followed including research approach, data collection and analysis techniques in detail together with justifications for following the particular methods.

Chapter Four: Calculation procedure

This chapter describes the procure and basics followed in calculating the selected sustainability measures together with reasoning.

Chapter Five: Data Collection and Analysis

This chapter includes the presentation and analysis of collected data in order to fulfil the second and third objectives.

Chapter Six: Conclusions and Recommendations

This chapter concludes the achievements of research aim and the objectives and further includes recommendations and directions for future researches.

CHAPTER 02 LITERATURE REVIEW

2.1 Introduction

This chapter contains appraise of the existing literature on the subject matter. The chapter mainly comprises several sections appraising the literature on technical aspect of 3D printing including available technologies, remarkable projects with features, currently used materials and their thermal transmittance, printing process and equipment used. In additional the chapter appraise literature on other types of walls used in residential buildings of Sri Lanka and on sustainability measures for construction sector in order to provide the basis for further execution of the study.

2.2 3D Printing

3D printing involves a process that make physical objects from a three-dimensional computer-aided digital model, with a series of thin layers of material. The use of 3D printing in Construction industry ranges from single story simple houses to large commercial buildings with complex shape geometries. Using the 3D printing techniques, wall elements can be manufactured as extruded prismatic bodies without any changes to their dimensions over the full height. (Teizer, et al., 2018).

2.3 On-Site & Off-Site 3D Printing

3D printing of buildings can be done on-site or off-site. In the off-site method, the unit and components of the building are produced in the factory and fixed together on-site premises after transporting to the required location. In on-site method, units are printed on location without having to assembled later. (Yang, et al., 2018).

2.4 Available Technologies for 3D Printing of Building Components

There are several technologies available for 3D printing of building components.
They are as follows as per the published literature.

<u>Contour Crafting</u>: This method was invented by Dr. Behrock Khoshnevis as a result of his effort to streamline the construction process using Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM). It is a layered construction technology that can automate whole process of constructing a house including the

electrical and plumbing services, reinforcements, dry wall fixing, and insulations works (Allouzi, et al., 2020) (Khoshnevis, 2004). By using this method Dr. Behrock expected to lower the cost of construction, increase the construction speed, add exotic architectural features to the buildings without incurring and additional costs. The walls printed by the printer were hollow walls which are light weight and with better heat insulation characteristics. Further, it provides safer work environment within the construction industry and reduce the impact to the environment (Khoshnevis, 2004).

The time spent for printing and energy consumed by printer and its ancillary equipment are major factors that determine the cost of contour crafting. A stereolithography (STL) file fed to the printer using a computer is determining the print head coordinates, speed and pump speed which feeds the print head (Allouzi, et al., 2020).

D-Shape: This is another printing technique developed by Enrico Dini that is applied to print the construction components. This technique involves depositing a layer of powder and a binder alternatively until the required component is printed (Figure 2.1). The binder is placed frame by frame only where the powder has to be solid to create the final component. The excess material which does not bound by the binder is removed subsequently. (Allouzi, et al., 2020) (Bos, et al., 2016).

Figure 2.1: D-shape 3D printing (Bos, et al., 2016)

Concrete Printing. This method involves the depositing concrete or mortar layer by layer to produce final output. It must be done with smaller resolution. Printing with higher resolution will not allow to print fine details of the components (Allouzi, et al., 2020) (Figure 2.2).

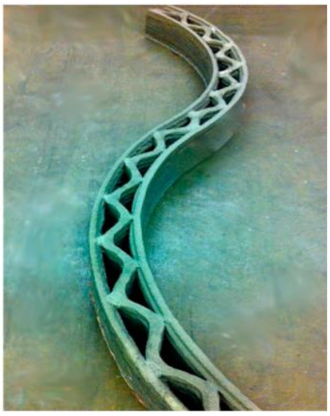

Figure 2.2: Concrete printing (Bos, et al., 2016)

2.5 Currently Used Materials for Printing

Different companies engaged in the 3D printing in construction industry claim that they have used different types of materials to success their printing process. Even though some mixes of material seem to be improbable, some material mixes show their potential in development as a better material in terms of the structural and mechanical properties and cost effectiveness. Ordinary concrete cannot be used in 3D printing due to the particle size, slump behavior in relation to the printer geometry. 3D printable concrete should be low slump, fast setting and it should allow for fast printing. The layer that was printed should be solid enough to take over the next layer. This requires extensive studies on properties of the material which are expected to be used for 3D printing. At the same time material properties such as shrinkage and creep also vital in deciding the best material for 3D printing. On the other hand, print size is an important factor while deciding the print process and the quality of the printed element (Bos, et al., 2016).

Many researchers have stated that construction waste and recycled materials can be used in the 3D printable material mix. This fact can be used to build economical, decent buildings using 3D printing technology (Wu, et al., 2016).

2.5.1 Materials used at Eindhoven University, Netherlands

Bos, et al., (2016) reported that Eindhoven university in Netherlands used a custom mortar for printing which was developed by SG Weber Beamix. The mortar is comprised of:

- Portland cement
- Siliceous aggregates
- Filler comprising with limestone
- Additives for increasing the flowability of fresh mortar and viscosity of mortar over time
- Polypropylene fibres.

The above mix was having a 30 N/mm^2 of compressive strength and a 5 N/mm^2 of tensile strength in 28 days. Accelerators and the cement limestone ratio were the determinant factors of the strength and the speed of gaining strength. However, the mix proportions of this mortar were not given in the study.

Several drawbacks were mentioned by Bos, et al. (2016) with regard to this mix. The buildability of layers is limited, as it depends on the relatively low stiffness and strength of the printed filament which is in presetting stage. Irregularities in the print filament were also observed which is another drawback that can leads to cavities in the filament (Bos, et al., 2016). Further, the author did not mention in detail what is the exact mix proportions of the ingredients.

2.5.2 Materials used by COBOD, in Denmark, Belgium and Middle East

COBOD, a Denmark company which involved in 3D printing of buildings, have published another mix used by them for printing an office building less than 50 m.

In order to achieve a better inter layer adhesion by allowing adequate time for the next layer to be printed on the previous layer, they have included cement around 30% of the weight of the mix (COBOD International A/S, 2020). The mix composition is stated in figure 2.3 below.

COBOD state their recipe is same as a traditional casted concrete. Due to the higher cement content in the mix, the unit price of the mix is slightly higher than the traditional concrete in the context of Denmark. Further, COBOD has indicated compression strength of the mix as 52 MPa. However, they have not measured the tensile strength of the mix which they assume to be one tenth of the compression strength. (COBOD International A/S, 2020).

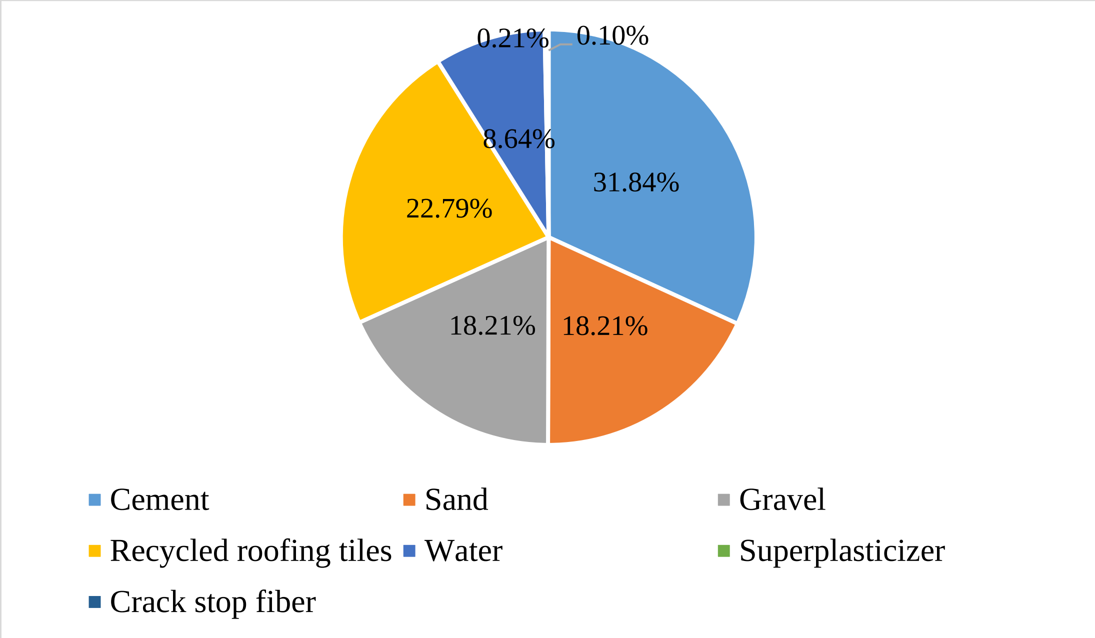

Figure 2.3: Material mix of COBOD by percentage weight of raw materials (COBOD International A/S, 2020)

2.5.3 Materials used at Loughborough University, UK

The mix tested in Loughborough University in United Kingdom consisted of sand and binder material consisting with a mix of CEM I cement, fly-ash, and undensified silica fume. (Le, et al., 2011) & (Le, et al., 2012)

They introduce polycarboxylate based superplasticizer to increase the workability and the strength of the mix. Similarly, a retarder comprises of amino-tris (methylenephosphonic acid), citric acid and formaldehyde is also added to maintain a sufficient open time and to facilitate a constant flow during printing. An accelerator, formed by sulphuric, aluminum salt and diethanolamine, was also investigated to control setting. Polypropylene micro fibres of 12/0.8 mm (length/diameter ratio) are added to avoid shrinking and deformation when dried.

Out of five mixes they have tried, Le, et al., 2012 concluded the following mix in table 2.1 proportion is the best mix in terms of extrudability, workability and the open time.

Table 2.1: Material mix stated by Le, et al., 2011

Components \ Mix	Mix Proportion (Kg/m3)
Binder: Cement	579 kg
Binder: Fly ash	165 kg
Binder: Silica Fume	83 kg
Fine aggregate (Sand)	1241 kg
Coarse aggregate	-
Water	216 kg
Water Cement Ratio	0.26

Le, et al. (2012) considered the mix consist with lowest content of binder that can be printed and built with recommended dosage of fibres 12/0.8 mm from the supplier (1.2kg/m3) and gain target strength. This mix has a 60:40 sand: binder ratio, where the binder is comprising 70% cement, 20% fly ash and 10% silica fume, plus 1.2 kg/m^3 micro polypropylene fibres. The water: binder ratio is 0.26 and the water–cement ratio was therefore 0.37. This mix also include 1% superplasticizer and 0.5% retarder, by weight of binder.

The printed concrete had a density of 2350 kg/m3, compressive strength of 75–102 MPa, flexural strength of 6–17 MPa depending on testing direction. The tensile bond strength between layers were varying between 2.3 to 0.7 MPa. The mix can be printed with 9 mm nozzle while the open time is 100 minutes (Le, et al., 2011).

Mahadevan, et al. (2020) also used this mix for their calculation done in India regarding the operational energy and operational carbon emission of 3D printed buildings.

Further, Le, et al. (2012) had carried out comprehensive testing of several 3D printable concrete mixes to define which had the best workability and usability (Alhumyani, et al. , 2020), . These mixes are stated in Table 2.2. Other studies used Le et al. (2012a) as a starting point to develop their new mixes such as (Labonnote, et al., 2016); (Ngo, et al., 2018).

Table 2.2: Different 3D printable material mixes and their densities (Alhumayani, et al., 2020)

	Nerella and Mechtcherine, (2016)		Le et al. (2012b)		Anell (2015)		Agustí-juan et al. (2017)	
	Kg/m3	%	Kg/m3	%	Kg/m3	%	Kg/m3	%
Cement	430	19.5	579	25	659	30	500	20.5
Fly-ash	170	7.7	165	7.1	87	4	0	–
Silicafume	180	8.1	83	3.6	83	4	43.5	1.8
Sand/aggregates	1240	56.1	1241	53.5	1140	52	1713	70.5
Water	180	8.1	232	10	228	10	169	7.
Superplasticiser	10	0.5	16.5	0.7	11.6	0.5	4.32	0.2
Fibre	0	–	1.2	0.05	1.2	0.05	0	–
Total density	2210		2318		2210		2430	

2.6 Shape of Printing

The wall elements are generally printed in a truss like geometry which can be a self-reinforced structure. That can provide the strength up to a certain level and reduce the reinforcement requirement for the structure. (Alkhalidi & Hatuqay, 2020)

2.7 Thermal Transmittance of Materials

Alkhalidi & Hatuqay (2020) designed distinct printable wall configurations with different materials to identify the wall configuration and materials that best suits to different climatic zones in the world. These configurations are shown in figure 2.4. Their research was focused on using the features of the 3D printed concrete walls to avoid further energy reduction treatments which is called passive energy reduction. (Alkhalidi & Hatuqay, 2020)

Building envelop must have a certain thermal transmittance value to create the thermal comfort in the building. 3D printed concrete walls may be the best solutions to achieve this thermal transmittance value as 3D printed concrete walls have a greater flexibility in creating the air cavities and insulation layers. Further, to achieve the most suitable thermal transmittance value multiple rows of the wall configuration can be printed using 3D printers (Alkhalidi & Hatuqay, 2020).

For structural considerations, the proposed configurations were based on the actual executed 3D printed concrete walls. The cavity to concrete ratios of 1:2.5 and 1:4

mentioned in the literature are commonly used. The different analyzed configurations details are shown in following figure 2.4 (Alkhalidi & Hatuqay, 2020).

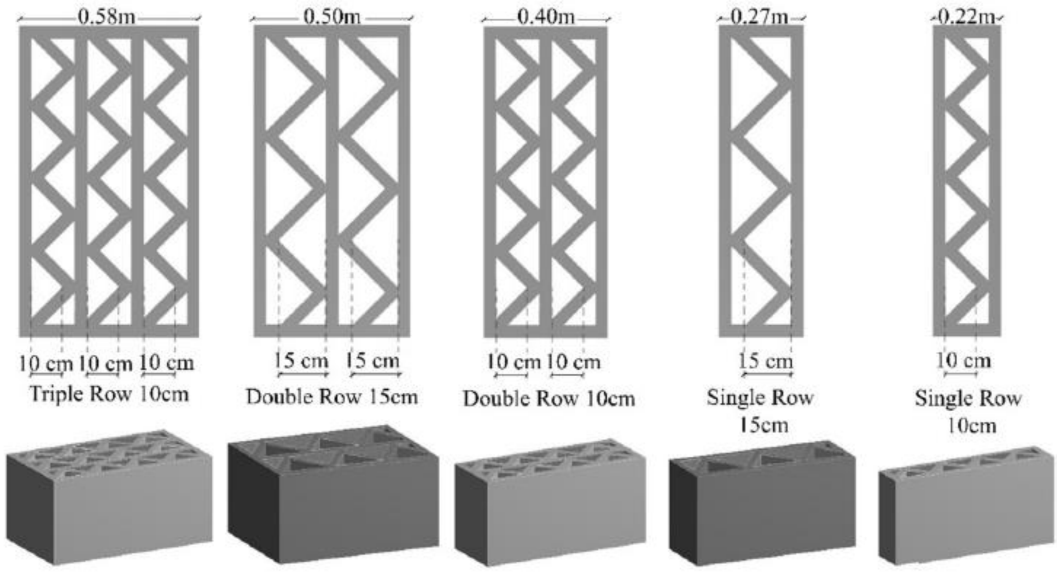

Figure 2.4: Different wall configurations analysed by Alkhalidi & Hatuqay, 2020

Three types of materials were selected for their study. They were sulphur concrete, cork concrete which could be printed with the material with concrete printing method and bound silica which is suitable for binder jetting (D-shape) method.

Using his analysis, Alkhalidi & Hatuqay (2020) prepared a 3D printing guideline that shows the best configuration, materials, and infill material for different regions of the world. They concluded single raw cavity wall made with cork concrete with 22 cm thickness and filled with E-PLA is the best configuration for equatorial countries. The thermal transmittance (U value) of that configuration is 0.52 W/m^2.K. Moreover, in their analysis they have found that U value of the cork concrete with 220 mm wall thickness is 1.76 W/m^2.K (Alkhalidi & Hatuqay, 2020). The single raw configuration is shown in figure 2.5.

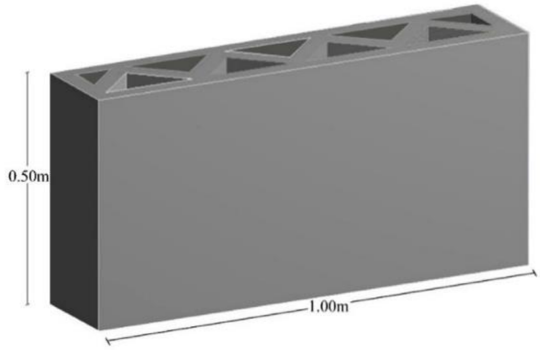

Figure 2.5: single row wall configurations analysed by Alkhalidi & Hatuqay (2020)

2.8 The Printing Process

The 3D printing process can be sub divided into three stages, as follows.

1. Data preparation – In this stage the element that should be printed is designed as a 3D CAD model. Then it is converted in to a STL file format which slices the model in to required layer height. Then it is converted into a G-code file which determine the print head path.
2. Concrete preparation – In this stage printable concrete is mixed and placed in the container.
3. Component printing – Concrete printing involves conveying the mixed concrete through pumps, pipes and nozzles and print the filament layer by layer until the element is fully printed. (Le, et al., 2012)

The process can be depicted graphically as in figure 2.6

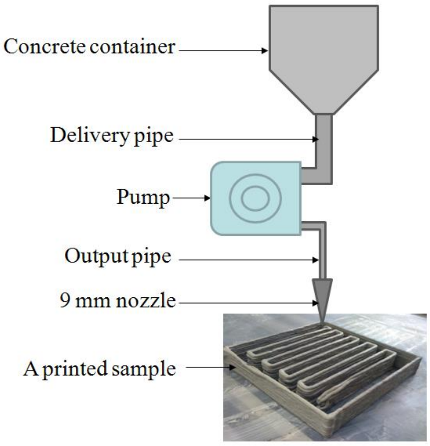

Figure 2.6: Component Printing process (Le, et al., 2012)

2.9 Equipment Used for 3D Printing

<u>Printers</u>

There are two major methods commonly used for printing walls of the building. They are (COBOD International A/S, 2020)

1. Gantry-type 3D printers (Figure 2.7) - for high volume prints on site.
2. Robotic arm 3D printers (Figure 2.8) - for smaller, more complex components. However, currently this technology is also used for printing larger building components (Apis Cor, 2021).

Figure 2.7: Gantry type 3D Printer

Figure 2.8: Robotic Arm 3D Printer

With the ability to move the print head along X axis, X axis along Y axis and Y axis on Z axis, the print head can move to any coordinate three dimensionally within the printable limits of the printer. Hence, the entire building can be printed by setting up the printer at once without having to move or calibrate printer repeatedly. (COBOD International A/S, 2020). The X, Y, and Z axis configuration of the gantry printer are shown in figure 2.9.

The robotic arm printer has additional movement since its pivoted at a centre point of the print. Opposed to having a large robot, Institute of Advance Architecture of Catalonia in 2014 invented printing concrete with small group of robots. These robots were aware of their relative position using sensors and synchronized to work together. (Bos, et al., 2016)

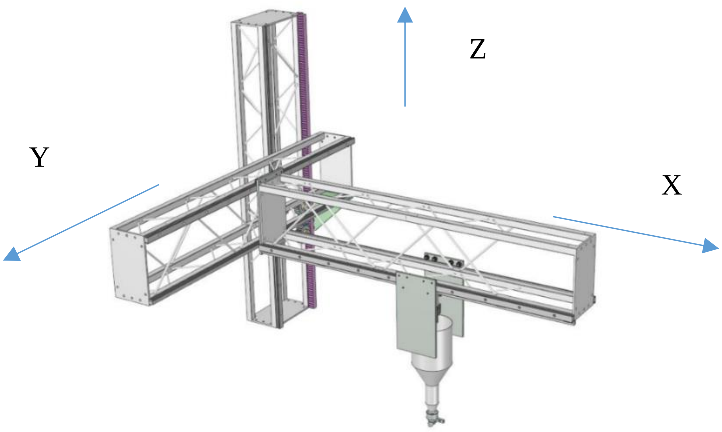

Figure 2.9: X, Y & Z axis of a gantry type printer (COBOD International A/S, 2020)

These two types of printers can be used for different applications which they are best for. Table 2.3 describes the best applications of the two types of printers (COBOD International A/S, 2020). However, there are occasions which these applications are different from the general categorization (Apis Cor, 2021)

Table 2.3: Use of 3D printers

Gantry Printer	**Robotic Arm Printer**
Printed on the final location	Printed within factory premises and delivered to site
Printing large quantities with higher speeds (E.g. complete buildings)	Printing lower quantities with complex shapes (E.g. specific parts of the building)
Used for general constructions with lower costs	Used for specialized constructions with higher costs

Both type of printers similarly extrudes concrete or mortar in layer upon layer building the structures from bottom to top according to the pattern fed to printer using a design and slicing software (COBOD International A/S, 2020).

<u>Gantry Type Printers</u>

Gantry printers use a print head to deposit the print materials in a controlled manner (Figure 2.10). In order to have a uniform deposition BOD printer, the print head consist with flaps and keep the deposition direction at a ninety degrees angle to a print head moving direction (COBOD International A/S, 2020).

Figure 2.10: Print head of a gantry type printer

The Z axis columns of the gantry type printer are normally mounted on a stable surface as shown in figure 2.11 (COBOD International A/S, 2020). The size of the print area can be increased by attaching additional gantries to X, Y and Z axis. The printer used at the Eindhoven University of Technology serves a print area of 9 x 4.5 x 2.8 m using a motion-controlled gantry robot. (Bos, et al., 2016). This is shown in figure 2.12.

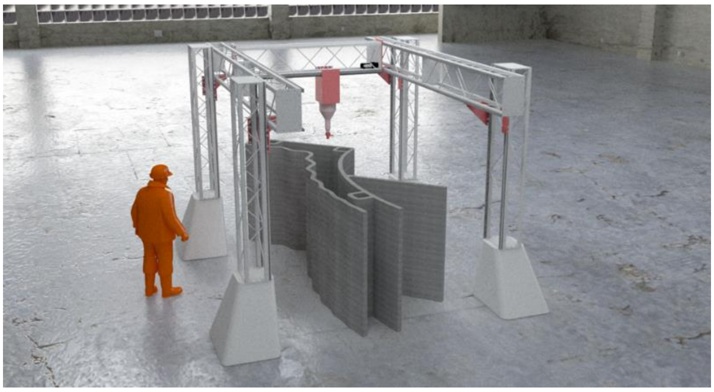

Figure 2.11: BOD printer mounted on a stable floor (COBOD International A/S, 2020)

A forklift and 2 -3 people are required to disassemble and move the printer modules. A small truck is required to move the printer parts from place to place (COBOD International A/S, 2020).

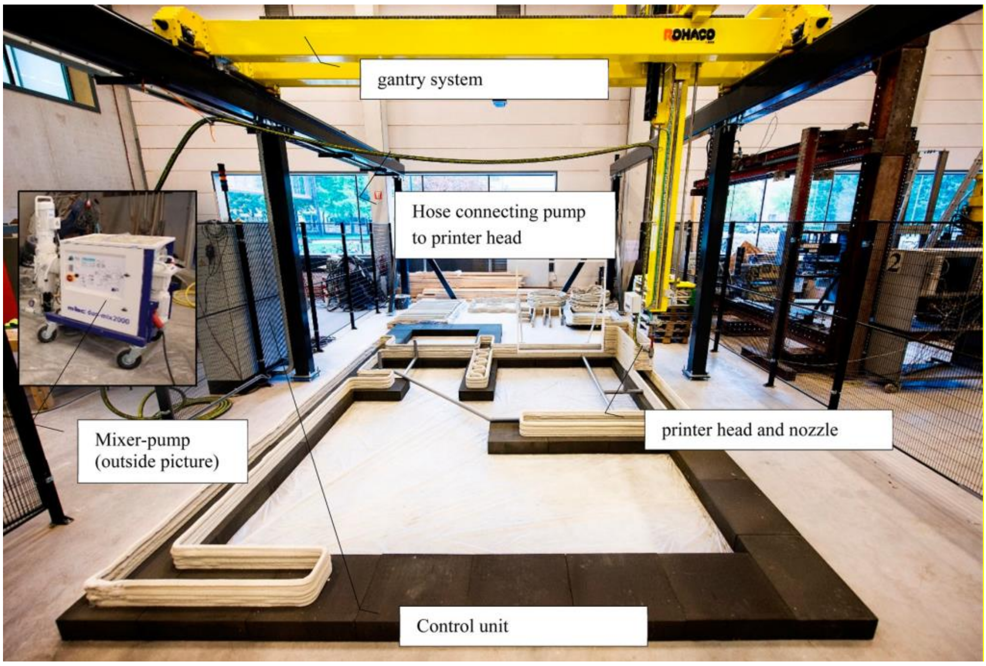

Figure 2.12: Printer in Eindhoven University of Technology (Bos, et al., 2016)

Material Handling System

In order to feed the material to the printer a material handling system should be available. Using the same material mix is forced towards the print head (Bos, et al., 2016). As an example, a BOD 2 printers material handling system, consist following components.

1. Material silo with 4 cubic meter capacity
2. Material mixer and progressive cavity pumps (PCP)
3. 20 m long hoses (50 mm diameter)

The pump speeds are adjustable according to the printer speed and the size of the aggregates. Pumps can deliver particle sizes to a maximum of 12 mm. However, the general particle size recommended is 8 mm. The material handling system used for BOD 2 is shown in figure 2.13.

Figure 2.13: Mixing pump used with COBOD printers

The BOD printers also have a storage and a pump at the print head to regulate the material flow, speed of printing at corners and curves and to deal with irregularities in the material flow from PCP pumps (COBOD International A/S, 2020).

2.10 Print Speed

The COBOD guarantee a print speed of 10 cm per second practically, even though the print head can be moved 1 m per second (COBOD International A/S, 2020).

The printer used at Eindhoven University also has reported a print speed of 10 cm per second even though it can move along the X, Y and Z axis at a 1.8 m per second and rotate along Z axis 3.0 rad/s. While printing the corners, this print speed is reduced depending on the radius of the curve.

The print head speed is interrelated with nozzle opening size and pump frequency. Further, all these factors are dependent on the water cement ratio and mix composition. (Bos, et al., 2016).

2.11 Research Data on the Other Types of Walls Used in Residential Buildings of Sri Lanka

When evaluating 3D printed concrete walls in terms of its Life Cycle Cost, Embodied Energy and the Carbon Footprint, it is important to compare those data with other walls type that are being used in Sri Lanka or under research. From that, 3D printed concrete walls can be correctly positioned among other wall types in terms of those criteria.

Accordingly, the data obtained from the research work of Udawatta, 2018 and Arooz & Halwatura, 2019 was used for both building up the life cycle cost of 3D printed building and comparing the results with the model house with other wall types. The summary of life cycle cost data published in the same research work is shown in table 2.4.

Similarly, for comparing the embodied energy of 3D printed concrete walls with other wall types published data on was used. These data are shown in figure 2.14.

Table 2.4: Life cycle cost data published in research work of Udawatta, 2018

Item and life span	Description	BB	CB	CAB	MCB	CSEB	FSEB
Foundation	Initial Cost	$ 390.33	$ 390.33	$ 390.33	$ 390.33	$ 390.33	$ 390.33
<60 years	Maintenance Cost	$ -	$ -	$ -	$ -	$ -	$ -
100%	Resale value	$ 390.33	$ 390.33	$ 390.33	$ 390.33	$ 390.33	$ 390.33
Wall (Square feet 1460)	Initial Cost	$ 3,434.61	$ 1,579.57	$ 1,333.49	$ 1,052.84	$ 2,866.07	$ 2,919.70
> 60 years	Maintenance Cost	$ 1,717.31	$ 1,579.57	$ 6,667.47	$ 1,052.84	$ 2,866.07	$ 2,919.70
		$ 0.00	$ 0.00	$ 0.00	$ 0.01	$ -	$ 0.01
	Resale value	$ 1,739.79	$ 1,105.70	$ 800.10	$ 968.61	$ -	$ 2,627.73
Front Concrete Column	Initial Cost	$ 70.00	$ 70.00	$ 70.00	$ 70.00	$ 70.00	$ 70.00
> 60 years	Maintenance Cost	$ -	$ -	$ -	$ -	$ -	$ -
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
Roof Work	Initial Cost	$ 955.04	$ 955.04	$ 955.04	$ 955.04	$ 955.04	$ 955.04
35 years	Maintenance Cost	$ 64.59	$ 64.59	$ 64.59	$ 64.59	$ 64.59	$ 64.59
	Resale value	$ 744.93	$ 744.93	$ 744.93	$ 744.93	$ 744.93	$ 744.93
Doors & Windows	Initial Cost	$ 426.00	$ 426.00	$ 426.00	$ 426.00	$ 426.00	$ 426.00
> 60 years	Maintenance Cost	$ -	$ -	$ -	$ -	$ -	$ -
	Resale value	$ 63.90	$ 63.90	$ 63.90	$ 63.90	$ 63.90	$ 63.90
Floor concrete	Initial Cost	$ 587.16	$ 587.16	$ 587.16	$ 587.16	$ 587.16	$ 587.16
> 60 years	Maintenance Cost	$ -	$ -	$ -	$ -	$ -	$ -
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
Bathroom	Initial Cost	$ 40.00	$ 40.00	$ 40.00	$ 40.00	$ 40.00	$ 40.00
30 years	Maintenance Cost	$ 3.98	$ 3.98	$ 3.98	$ 3.98	$ 3.98	$ 3.98
	Resale value	$ 1.39	$ 1.39	$ 1.39	$ 1.39	$ 1.39	$ 1.39
Electrical	Initial Cost	$ 126.67	$ 126.67	$ 126.67	$ 126.67	$ 126.67	$ 126.67
50 years	Maintenance Cost	$ 2.70	$ 2.70	$ 2.70	$ 2.70	$ 2.70	$ 2.70
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
Internal wall plastering	Initial Cost	$ 375.05	$ 375.05	$ 375.05	$ 375.05	$ 375.05	$ 375.05
only for paints	Maintenance Cost	$ -	$ -	$ -	$ -	$ -	$ -
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
External wall plastering	Initial Cost	$ 284.91	$ 284.91	$ 284.91	$ 284.91	$ 284.91	$ 284.91
	Maintenance Cost	$ -	$ -	$ -	$ -	$ -	$ -
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
Internal Painting	Initial Cost	$ 337.33	$ 337.33	$ 337.33	$ 337.33	$ 337.33	$ 337.33
6 years	Maintenance Cost	$ 1,913.19	$ 1,913.19	$ 1,913.19	$ 1,913.19	$ 1,913.19	$ 1,913.19
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
External Painting	Initial Cost	$ 161.33	$ 161.33	$ 161.33	$ 161.33	$ 161.33	$ 161.33
6 years	Maintenance Cost	$ 915.01	$ 915.01	$ 915.01	$ 915.01	$ 915.01	$ 915.01
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
Septic tank	Initial Cost	$ 146.67	$ 146.67	$ 146.67	$ 146.67	$ 146.67	$ 146.67
30 years	Maintenance Cost	$ 14.58	$ 14.58	$ 14.58	$ 14.58	$ 14.58	$ 14.58
	Resale value	$ -	$ -	$ -	$ -	$ -	$ -
Total initial cost		$ 7,335.09	$ 5,480.05	$ 5,233.97	$ 4,953.32	$ 6,766.54	$ 6,820.17
		$ 4,631.35	$ 4,493.62	$ 9,581.52	$ 3,966.89	$ 5,780.11	$ 5,833.74
Total Resale value		$ 2,940.34	$ 2,306.25	$ 2,000.65	$ 2,169.16	$ 1,200.55	$ 3,828.28
Energy cost		$ 18,799.49	$ 20,359.55	$ 23,569.68	$ 19,444.52	$ 19,924.54	$ 21,939.13
Over heads		$ 586.81	$ 438.40	$ 418.72	$ 396.27	$ 541.32	$ 545.61
Life cycle cost		$ 28,412.40	$ 28,465.38	$ 36,803.24	$ 26,591.82	$ 31,811.96	$ 31,310.38
****** one kilo watt equals 0.26$**							

The U-values of the walling materials are shown in the Table 2.5 as mentioned by Arooz & Halwatura (2019) and Udawatta & Halwatura (2016).

Table 2.5: U-Values of Walling Materials (Arooz & Halwatura, 2019)

Material	U-Value (W/m^{2}K)
Bricks	2.110
Cement Blocks	2.617
Cabook Blocks	2.688
Mud Concrete Blocks	2.315
Mud Concrete Walls	2.170

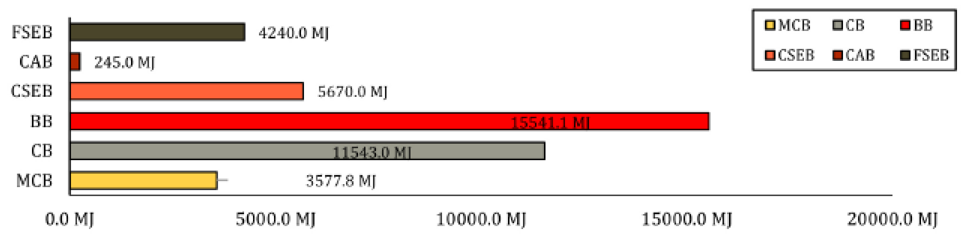

Figure 2.14: Embodied energy of different walling materials considering 100 square feet wall area (Udawatta, 2018)

2.12 Summary

At present, there are several 3D printing technologies available to print buildings or building components. Also, they can be printed on-site or off-site. Generally, gantry type of printers is used for on-site printing while robotic arm printers are used for off-site printing.

Many researches can be found on different types of material recipes that can be used for 3D printing. The material mix published by Le, et al. (2011) is one of the frequently cited mix by other researchers.

Generally, 3D printed concrete walls consist with a truss like geometry. The best configuration of the 3D printed wall for equatorial countries interms of thermal transmittance is 220mm thick E-PLA filled cork concrete wall. The U-value of the same configuration without the E-PLA filling is 1.76 W/m^2.K.

Researches can be found which have compared the life cycle cost and embodied energy of different walling materials used in Sri Lanka. 3D printed concrete walls also required to be included in those comparisons in order to find out where it stands among other wall types in terms of Life Cycle Cost and Embodied Energy.

CHAPTER 03 RESEARCH METHODOLOGY

3.1 Introduction

This chapter discusses the methodology adopted for this research study. It illustrates the total research process and subsequently describes the research methodology including research approach, data collection and analyzing techniques in detail.

3.2 Research Process

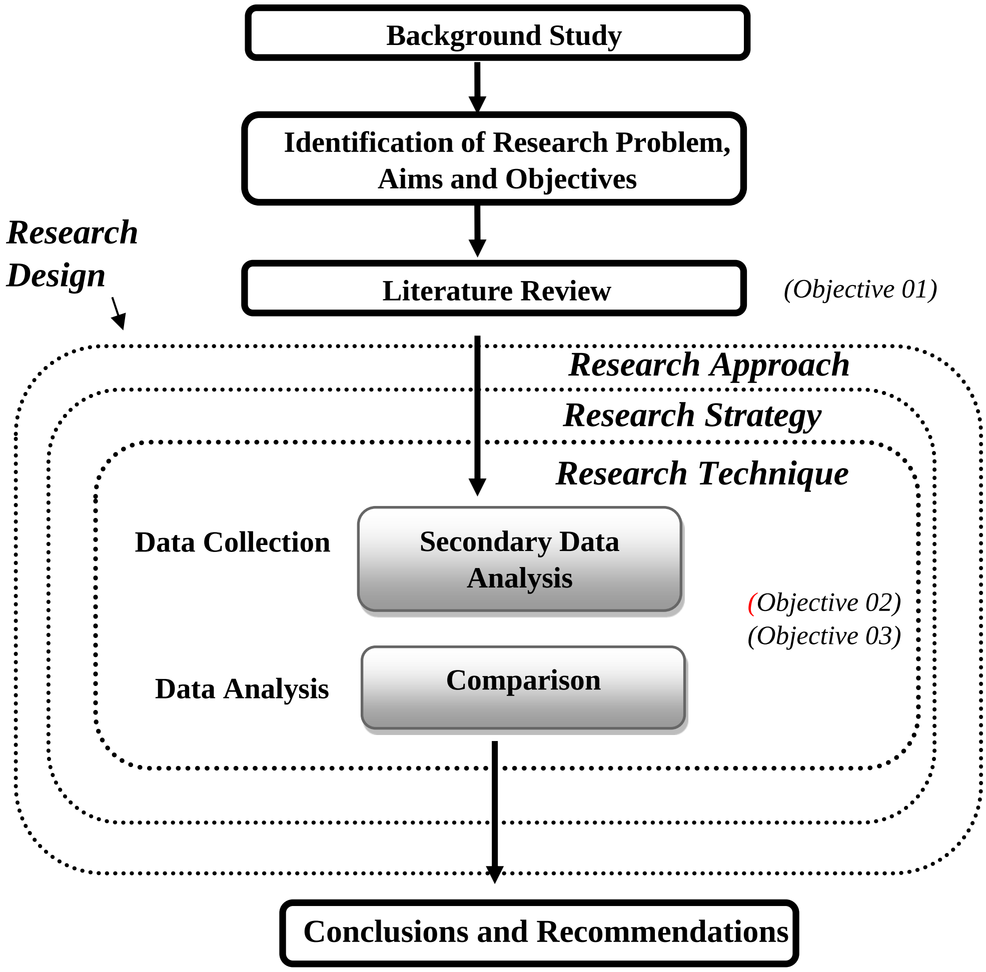

Figure 3.1 Research process

Research process is the series of steps organized in the sequence that is necessary for the effective execution the research (Kothari, 2004). The research process to be adopted in this study is illustrated in Figure 3.1.

3.3 Research Design

Research design is the systematic procedures to solve the research problem by linking data collection and analysis to results and thereby to conclusions (Fellows & Liu, 2008). Research design may be quantitative which deals with numerical data or may be qualitative with analysis of complex data in terms of its content or narrative interpretation (Taylor, 2010).

The research design of this research study is developed throughout the following sub sections.

3.3.1 Research approach and research strategy

Research approach can be broadly divided into two categories namely quantitative approach and qualitative approach.

This research study follows quantitative research approach. Qualitative approaches tend to seek gathering factual data and to study relationships between facts and analysis of the data to yield quantified results (Fellows & Liu, 2008).

3.3.2 Research technique – Data Collection and Analysis

'Secondary data analysis' is the data collection technique adopted for this research study. Secondary data analysis involves analysis of data collected by others usually for different purposes (Chivaka, 2018).

However, unlike most other researches which analyse bulk secondary data sets to come up with the conclusion, this research compares the results of the calculations with the available research findings. Further, in order to make the calculation comparable, the calculations of this research followed the similar basis to other researches. The arrangement is detailed in the Chapter 4.

3.3.3 Reasoning behind the selection

3D printing is a modern technique that has never been used in the construction industry in Sri Lanka. According to Chivaka, (2018) secondary data analysis is principally used in the researches when the secondary data are the only available data. Further, according to the author, there are economic reasons behind the deletion of secondary data analysis since the method is cost effective and less time consuming. If not used the secondary data, this research would not have been viable. Although some people argue on the less credibility of data, such problem does not exist with this research because data extracted from published research papers in indexed journals and conference proceedings was used in this research.

3.3.4 Indicators and data

Sustainable construction has three main dimensions: environment, social and economic. Each of these dimensions can be characterised by number of indicators. (Danso, 2018).

Since housing for all itself is an indicator of social sustainability, this research was focused on collecting data to assess the economic and environmental sustainability of 3D printed concrete walls.

Initial cost alone does not indicate the economic sustainability. Accordingly, Life Cycle Cost (LCC) which represent total cost of ownership of a facility through its lifetime is selected as the indicator for economic sustainability.

Embodied Energy (EE) and building Carbon Footprint are the key measures used to ascertain the environmental sustainability in the construction sector. However, considering the availability of comparable data in the past researches on the other walling types, Embodied Energy (EE) was used as the main indicator to assess the environmental sustainability of 3D walls in this research. Building Carbon Footprint was used additionally in order to further analyze the environmental sustainability dimensions of 3D printed concrete walls and for further research directions.

Life Cycle Cost (LCC)

The total cost of ownership of a facility through its lifetime can be defined as the Life Cycle Cost (LCC) of that product (National Institute of Building Sciences, 2010). LCC includes the cost of planning, design, acquisition, operation, maintenance, and disposal. The residual value of the product at the end of its life cycle is deducted from the LCC (Arooz & Halwatura, 2019) . Hence calculation of the life cycle cost can be depicted in the following formula.

LCC = Ic + (Mc + Ec + Cc + Oc) + Uc – Rv (Sassi, 2006)

Ic = Initial Cost

Mc = Maintenance Cost

Ec = Energy Cost

Cc = Cleaning Cost

Oc = Overhead Cost

Uc = Utilization Cost

Rv = Resale Value

Accordingly, economic sustainability diminishes as the LCC increases.

Embodied Energy

Embodied Energy of a building means all the energy required to produce the materials used for the building. It comprises the energy required in mining, manufacturing, transporting materials and the services used for such processes. Hence lesser the embodied energy, higher the environmental sustainability of the facility. (Ding, 2007)

Carbon footprint

Carbon foot print represent the total amount of greenhouse gases produced throughout the life-cycle of a building. Therefore again, lesser the carbon foot print, higher the environmental sustainability of the facility.

3.4 Summary

This chapter described research methodology used to achieve (*objective 02) and* (*objective 03)*. The research methodology adopted was secondary data analysis approach with data collected from other research findings.

CHAPTER 04 CALCULATION PROCEDURE

4.1 Introduction

In order to compare the environmental and economic sustainability of 3D printed concrete walls against the other wall types, the calculations of sustainable indicators should follow the same procedures and basics of previous researches. Accordingly, this chapter describes the procedure and basics followed in calculating Life Cycle Cost (LCC), Embodied Energy (EE) and Embodied Carbon (EC) with reasoning.

4.2 Selected Building Model for Analysis

The same house model used by Arooz & Halwatura (2019) and Udawatta & Halwatura (2017) was used for this research also. Details of the published house plan is figured as 4.1.

Figure 4.1 Selected House Model

Floor Area	:46.4 m^2 (500 sqft)
Spaces	:Two bedrooms, Living and dining area, Kitchen, separate bathroom
Fittings	:10 light points, 7 power points and the fan points

4.3 Calculating Life Cycle Cost

Udawatta (2018) had annexed an element wise cost breakdown for above costs, for many walling materials. Hence this breakdown was required to be adjusted focusing the walling material in order to derive the LCC of the model house built with the 3D printed concrete walls. Above costs related to the 3D printed concrete walls were required to be calculated and the adjustment to costs of related elements required to be made. Since the plastering is not required (Iconbuild, 2022), (COBOD International, 2022) for 3D printed concrete walls the related costs shall be removed from the breakdown. Initial wall costs were replaced by 3D printed wall cost while maintenance cost of the walls was removed due to the reasons mentioned in the following sections.

Arooz & Halwatura (2019) had used a net present value (NPV) based methodology to calculate the life cycle cost of the building. The same methodology was used in this research as well. The following formulas were intended to use for discounting the energy cost of the building. However, since the inflation and the interest rates are almost similar (Arooz & Halwatura, 2019) (Central Bank of Sri Lanka, 2018) in year 2017 simple payback was used to discount the same.

$$NPV = \sum_{t=0}^{T} \frac{Ct}{(1+r)^t}$$

Ct = Estimated cost of year t
R = Discount rate
T = Period of Analysis

$$NDR = \frac{1 + int\%}{1 + inf\%} - 1$$

Int% = interest rate
Inf% = Inflation rate

4.4 Calculating Initial Cost of 3D printed concrete walls

Initial wall cost can be divided into several categories. The breakdown of the cost can be depicted as in figure 4.2.

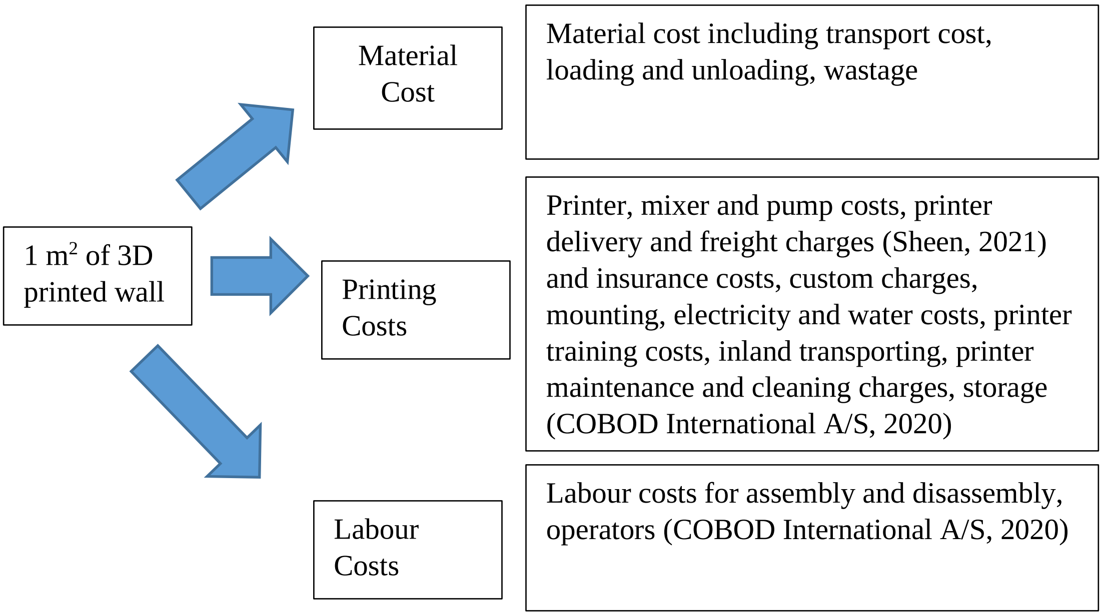

Figure 4.2: Cost breakdown in 3D printed wall

The walling material cost of 3D printed building was calculated by Allouzi, et al. (2020) in Jorden. They have modeled the building in Autodesk Revit and calculated the volume of concrete required for printing the entire wall area. Accordingly, in this research, 20 m^2 of wall section was modelled in Revit and volume of concrete required for 1m^2 of wall area was calculated using the ITWO CostX software. This is shown in figure 4.3. The same was multiplied by the total area of the model house in order to obtain the total volume of concrete required for the model house.

It was assumed that the material mix published by Le, et al., 2011 was used to print the walls of house model. The weight required of the basic materials were calculated from the mix proportion. Market rates in 2018 were used to obtain the material cost of the 3D printed wall, since the data in comparison are also published in year 2018.

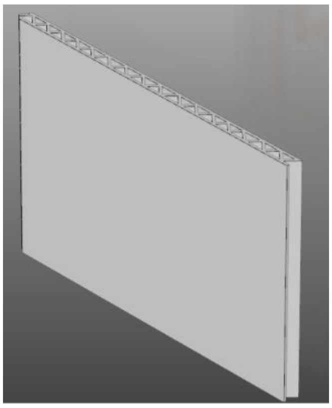

Figure 4.3: iTwo CostX measuring the volume of concrete per 1 m^2 of 3D printed wall

Allouzi, et al. (2020) had generated a sliced model of building (stereolithography file - STL) using Autodesk Revit software. Using the same the print head path is determined, and the actual print time is calculated. However, Allouzi, et al., 2020 has not counted for the diagonal tool paths created in between the external and internal leaves of the 3D printed concrete walls. In order to account this the 3D printed concrete walls were designed in Autodesk Revit, converted to STL format and print was simulated in Ultimaker Cura in order to obtain the actual print time. Due to the scale of the print Ultimaker Cura didn't fully support the process and demonstrated 2 days and 4 hours print time for 500 sqft model house. The print simulation in Cura is shown in figure 4.4.

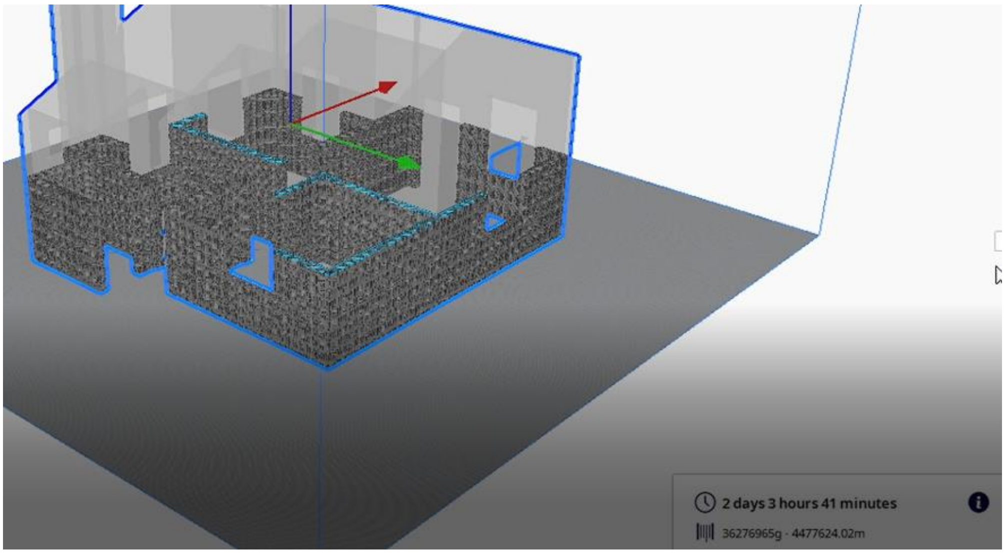

Figure 4.4: Print simulation in Ultimaker Cura

In addition, Table 4.1 indicates the print time data obtained from several actual scenarios.

Table 4.1: Research data on site print time calculation

No.	Building and Location	Size	Print time of walls reported	Citation	Time when converted to 500 sqft house
01	Vulcan, single-family house in Austin, Texas	800 sqft	24 hours	(Powell, 2018)	15.00 hours
02	House in Calverton, New York	1900 sqft	48 hours	(SQ4D, 2021) (Reuters, 2021)	12.63 hours
03	Model walls in Berlin Exhibition	86 sqft of wall area	1 hour	(Carlota, 2020)	17.00 hours (for 1,460 sqft wall area)

Considering all above data, output from Ultimaker Cura seems not sensible. The reason could be that in-built software of construction 3D printers can optimize the tool path better than Ultimaker Cura which is suitable for general-purpose small-scale prints. Further, No 1 ‘Vulcan, single-family house in Austin, Texas’ and No 2 ‘House in Calverton, New York’ do not contain any data on the wall area where the print time would be directly depends on the wall area. Accordingly, 17 hours were considered as the printing time for the selected house model on site based on ‘Model walls in Berlin Exhibition’ indicated in Table 4.1. These figures were taken for calculating electricity usage for printer, mixer and the pumps in the Analysis.

Still there are no data published on the lifetime of printer and its components. Therefore, it was assumed that printer and the components can be used for 10 years before disposal. Similarly, it was assumed that there is no salvage value of the printer and the components at the disposal. Hence if two working days (8 hours per day) are spent for printing a house, assuming 236 days are working days per year, 1,180 houses can be built using the 3D printer before its disposal. For simplifying the calculation this figure was rounded off to 1000. This figure was taken for analysis of printer cost for printing 3D printed concrete walls.

Freight charges were calculated using the freight charges calculators available on the internet. Inland moving of printer and the components were assumed to be within 20 Km. Percentage of custom charges applicable were obtained from the Sri Lanka Customs, 2021.

Labour required, operators and the training cost of the printer were obtained as per the COBOD International A/S, 2020.

4.5 Calculating Maintenance Cost of 3D printed concrete walls

As per Dias (2003) the useful life of the concrete was taken as 60 years. Therefore, a maintenance cost was not considered since the estimated concrete life is same as the building’s useful life. On the other hand, since the plaster is not required for a 3D printed wall as per the real-world examples shown in figure 4.5, the related maintenance cost was omitted.

Figure 4.5: Plastering is not required for 3D printed houses (Ozdemir, 2021) (STIRWorld, 2020) (ABC Wires, 2021)

4.6 Calculating Energy Cost of 3D printed concrete walls

The wall thickness and the pattern were assumed as single row 220 mm thick walls prescribed by Alkhalidi & Hatuqay, 2020 for equatorial countries. The cavity between walls were assumed remain unfilled to simplify the calculation. Even though the mix of materials used by Alkhalidi & Hatuqay, 2020 is slightly different from the material mix considered in this research, the U value of the wall was considered as 1.76 $W/m^2.K$.

The house model was designed in the Design Builder V.6 software and annual cooling load was calculated (figure 4.5). Thereafter, total energy cost was calculated over 60 years using NPV formula adjusted for the inflation (Arooz & Halwatura, 2019)

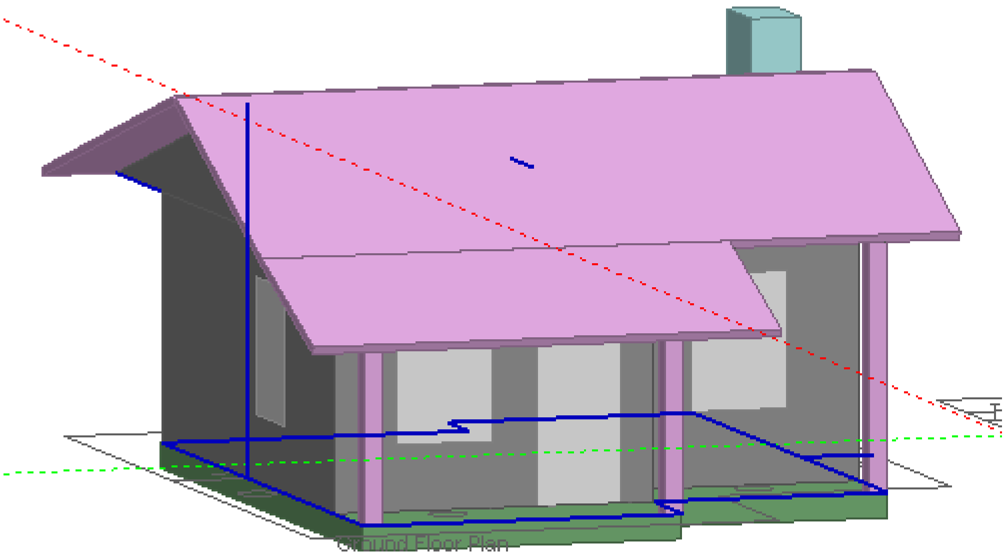

Figure 4.6: Design Builder V.6 model used for calculating energy cost

4.7 Calculating Resale Value of 3D printed concrete walls

Demolished concrete can be used as aggregate for roadbeds. 10% of volume of the concrete are considered wasted during the processing, due to geometry constraints, transportation and unexpected occurrences (Cadenazzi, et al., 2019). Therefore, in this research, 90% of the concrete volume was considered resold at the price of road paving aggregate (Aggregate base course).

Calculation of resale value of 3D printed concrete walls:

19 m3 x 0.9 x USD 26.67 per meter cube of aggregate base course = USD 456

4.8 Calculating Overhead Cost of Model House

Arooz & Halwatura (2019) and Udawatta & Halwatura (2017) had used 8% of the initial cost as the overhead cost of the building. The same was used in this research for the comparison purpose.

4.9 Calculating Embodied Energy

Researchers like Fay & Raniga (2010) and Dias & Pooliyadda (2004) discussed several methods of calculating embodied energy of building materials. Among them process analysis is the most widely used method that used for calculating embodied energy. Arooz & Halwatura (2019) and Udawatta & Halwatura (2017) also used this method to calculate the embodied energy of walling materials.

At each industry level, the inputs and outputs of the processes are identified. All the materials, equipment, and energy inputs are considered when determining the energy requirement of a process. They are identified and quantified for a given amount of output (Dias & Pooliyadda, 2004). Similarly, as per their research human energy was not considered due to the complexity and high ambiguity associated with human energy. Moreover, since the 3D printing process is mostly automated, human energy associated with the printing process is minimal. Hence most of the energy is captured in calculations despite the fact that human energy is not considered.

Similar to the embodied energy calculation made by Arooz & Halwatura (2019), the embodied energy for 3D printed wall was calculated based on the 10’ x 10’ area of 3D printed wall section. The section is 220 mm thick and assumed that materials mix proportion is as proposed by Le, et al., 2012.

Three forms of energy mentioned by Emmanuel (2004) was calculated according to the process identified above, using data from life cycle cost analysis and the secondary data published on the journals and energy databases. These forms of energy are (Emmanuel, 2004),

1.) Level 1: Embodied Energy in Raw Materials
2.) Level 2: Transport Energy for Raw Materials and Finished Products
3.) Level 3: Energy in Construction

Following are the assumptions made during the calculation of embodied energy:

1. Cement was delivered from a factory in Puttalam area with 152 Km distance from Colombo. This is same as the distance considered by Udawatta & Halwatura (2017).
2. Sand was delivered from Manampitiya area with 152 Km distance from Colombo. This is same as the distance considered by Udawatta & Halwatura (2017).

3. Flyash was delivered from Lakvijaya power plant with 174 Km distance from Colombo.
4. Water is obtained for the process by a water pump with a 125 L/Min capacity and 200 W water pump.
5. Silica fume, Flyash, and Superplasticizer are imported materials
6. Printer was assumed delivered from Denmark, with a distance to Colombo port 14,000 Km
7. Fuel efficiency of the lorry was assumed as 8 Km/L
8. Fuel efficiency of the forklift was assumed as 8 Km/L

Table 4.2 shows the data that were used to calculate the embodied energy of 3D printed concrete walls.

Table 4.2: Data that were used to calculate the embodied energy of 3D printed concrete walls

Material	**MJ per Kg**				**Reference**
	Biomass	**Fossil Fuel**	**Electricity**	**Imports**	
Cement		3.681	0.601		(Dias & Pooliyadda, 2004)
Silica Fume				0.036	(Aysha et al., 2014)
Sand					(Dias & Pooliyadda, 2004)
Fly ash		0.100			(Girgin, 2014)
Polypropylene Fibre				95.400	ICE Database V.2
Water			0.096		(Arooz & Halwatura, 2019)
Superplasticizer				9.000	(Aysha et al., 2014)

4.10 Calculating Carbon Footprint

The embedded energy of the 3D printed wall is comprising of the embedded energy of raw material, transportation energy of the materials and equipment and the production energy, as discussed above. These energy categories can be further classified according to the input energy, namely: biomass, fossil fuel and electricity (Dias & Pooliyadda, 2004).

The carbon emission of imported items was calculated using the 0.02 kgC per MJ. This factor account for contribution of all types of energy sources for producing the imported materials (Dias & Pooliyadda, 2004). The conversion factors that were used by Pooliyadda (2000) are listed in table 4.3.

Table 4.3: Factors used for Carbon Emission Calculation of 3D printed concrete walls

Energy Source	**CO_2 Emission Rate KgC/MJ**	**Original Reference**
Fossil Fuel	20.3/1000	(Turbott, et al., 1991)
Biomass (Actual) Biomass (Effective)	15/1000 0	(Turbott, et al., 1991) (Honey & Buchanan, 1992)
Electricity (Based on 34% Thermal)	18.36/1000	(Turbott, et al., 1991)
Imports	0.02	(Turbott, et al., 1991)

4.11 Summary

The same house model used by Arooz & Halwatura (2019) and Udawatta & Halwatura (2017) with 500 ft^2 floor area was used for this research in order to make the results comparable. In addition, this chapter presented data and parameters considered from the previous researches for the calculations.

CHAPTER 05 ANALYSIS AND DISCUSSION OF RESULTS

5.1 Introduction

Previous chapter included the calculation procedure adopted in the research. This chapter present the results of the calculations and compares the results with other wall types leading toward the conclusions.

5.2 Printing Process of 3D printed concrete walls

According to Le, et al. (2012) and COBOD International A/S (2020) the print process on site can be elaborated as below for the purpose of initial cost calculation and embodied energy calculation.

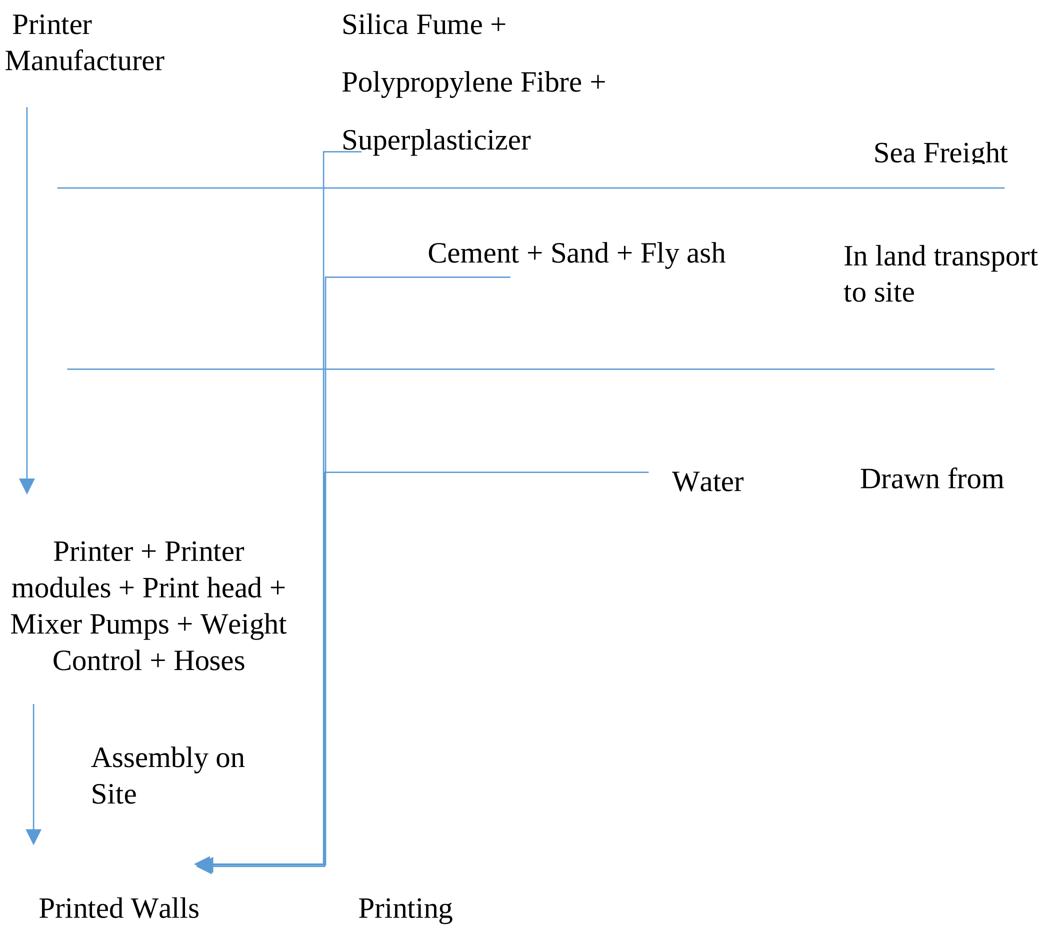

Figure 5.1: Printing Process of a 3D printed wall

(Le, et al., 2012 and COBOD International A/S, 2020)

5.3 Printing cost of the house

The analysis of print cost for 2017, per house is attached in Annexure – 1, together with the assumptions made for calculation. As per the calculation, print cost per house in 2017 is USD 808. The rate breakdown for the 3D printed wall is attached in Annexure -2. The cost proportions of the material, plant and labour of 3D printed wall are shown in figure 5.1. The main cost component of 3D printed concrete walls is material cost which represent 82% of wall construction cost while equipment cost and labour cost represent 16% and 02% respectively. 02% of the labour proportion is involved for assembly and disassembly of the printed and equipment.

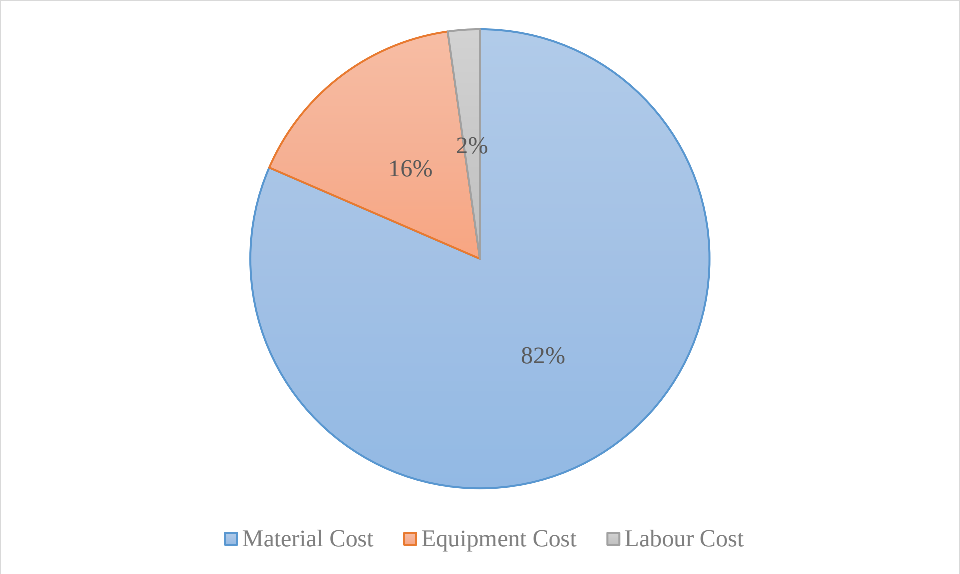

Figure 5.2: Material, Plant and Labour Proportions of the 3D printed concrete walls

The supply and printing cost of a meter cube of the fibre reinforced high-performance concrete is USD 324, in Sri Lanka in 2017. Supply and laying cost of ordinary grade 25 concrete including formwork and reinforcement was around USD 385 in the same context. The difference is graphically shown in figure 5.3 below. The reason could be using a higher proportion of fly ash, elimination of formwork and reinforcement bars.

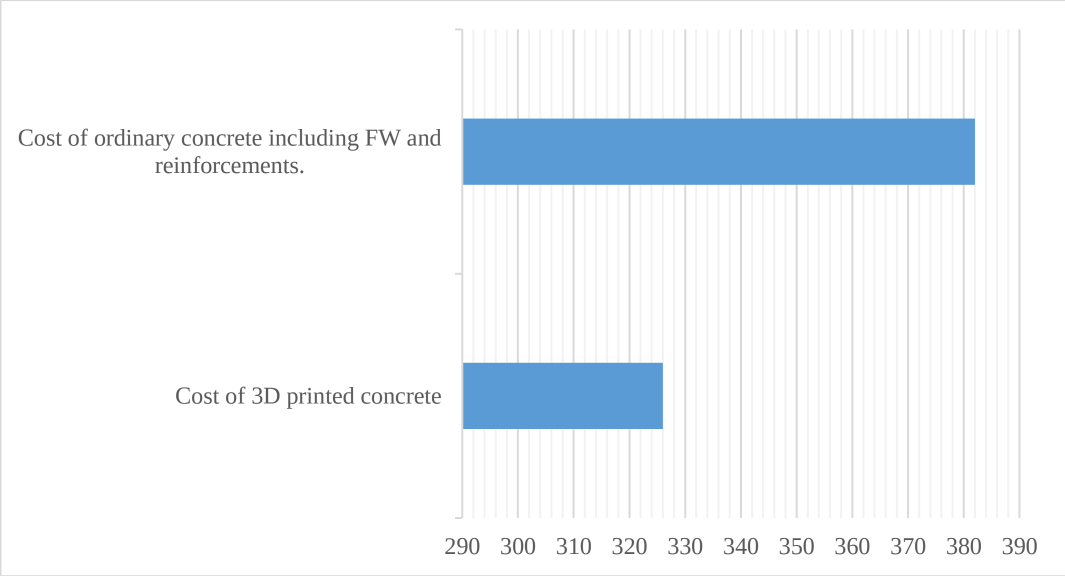

Figure 5.3: Comparison of ordinary concrete construction vs. 3D printed concrete walls

5.4 Comparison of Initial Cost of Model House

As per the analysis, the initial cost of the 3D printed house is the highest compared to other types of walls. Table 5.1 compare the initial cost of 3D printed house with the data obtained from Udawatta, (2018). Initial construction cost of the considered model house ranges between USD 3885.20 – USD 7335.09 in 2017 if other walling materials are used whereas the figure increases to USD 9444.53 with 3D printed concrete walls (Refer to Annexure -3).

Table 5.1: Comparison of initial cost of model house with 3D printed concrete walls vs. other wall types

Walling Material	**Initial Cost of Houses (2017 prices) USD**	**Reference**
Bricks	7,335.09	(Udawatta, 2018)
Cement Blocks	5,480.05	
Cabook Block	5,233.97	
Mud concrete block	4,953.32	
Mud Concrete Walls	3,885.20	
Cement Stabilized Earth Blocks	6,766.54	
Fly ash stabilized earth block	6,820.17	
3D printed concrete walls	**9,444.53**	

Hence, it could be observed that 3D printed concrete walls have the highest initial cost compared to the other walling types that are frequently used and innovative. This is subject to the assumptions made in the methodology chapter and compared using the prices in year 2017. The initial cost increase resulted by using 3D printed concrete walls compared to alternative walling types are graphically represented in figure 5.4. The saving of the plaster cost is considered here since internal and external plaster works are not required for the 3D printed concrete walls. Using the diagram in figure 5.4 it could be identified that a significant cost increase (above 70%) is resulted compared to mud concrete walls, mud concrete blocks, cabook blocks and cement blocks. The initial cost increase of 3D printed concrete walls compared to cement blocks is 72% and Bricks is 29% which are the widely used walling types in Sri Lankan housing industry.

However, in order to make a final decision on the cost, other aspects of the life cycle cost also should be analysed.

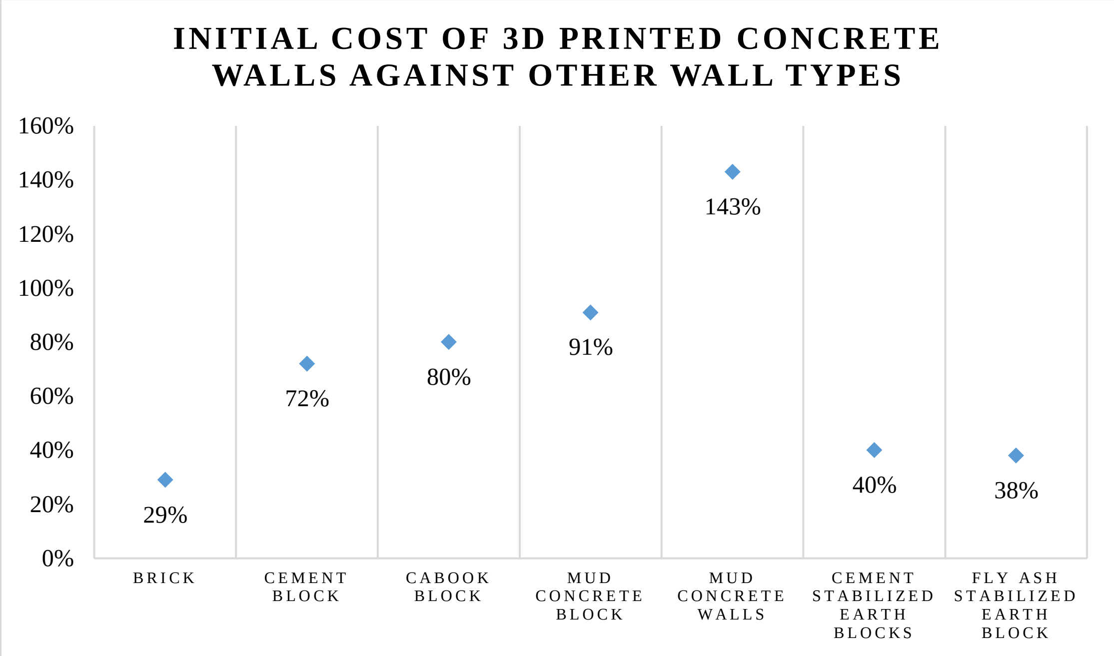

Figure 5.4: Initial cost with 3D printed concrete walls against other wall types

5.5 Comparison of Maintenance Cost

Table 5.2 and Figure 5.5 indicate the maintenance cost of the considered model house with 3D printed concrete walls and with other types of walls.

Table 5.2: Comparison of maintenance cost of model house with 3D printed concrete walls vs. other wall types

Walling Material	Maintenance Cost of Houses USD (2017 prices)	Reference
Bricks	4,631.35	(Udawatta, 2018)
Cement Blocks	4,493.62	
Cabook Block	9,581.52	
Mud concrete block	3,966.89	
Mud concrete walls	2801.70	
Cement Stabilized Earth Blocks	5,780.11	
Fly ash stabilized earth block	5,833.74	
3D printed concrete walls	**2914.05**	

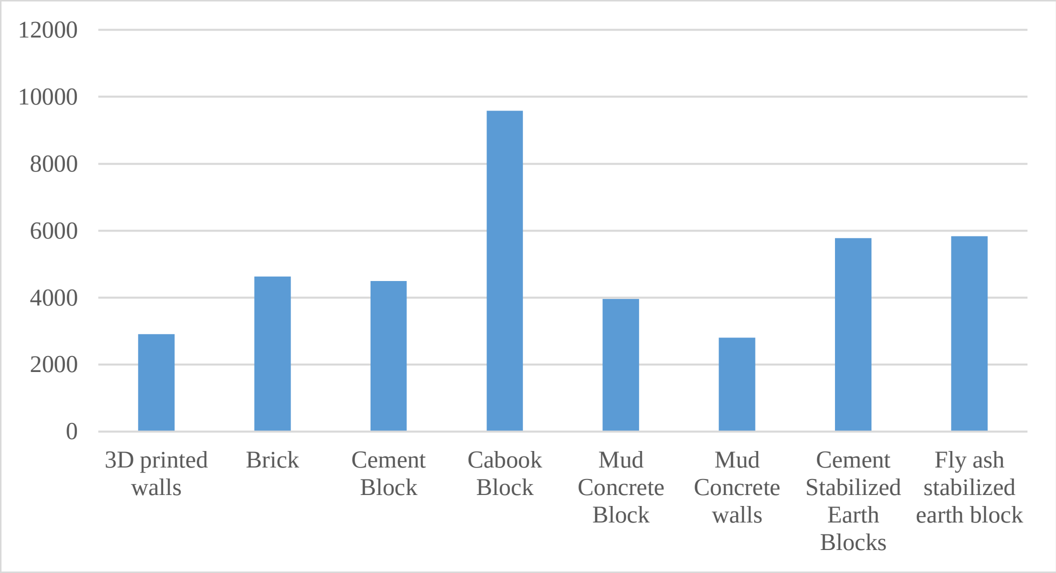

Figure 5.5: Comparison of maintenance cost of model house with 3D printed concrete walls vs. other wall types

Accordingly, the maintenance cost of the model house with mud concrete walls (USD 2801.70) is the lowest while 3D printed house becomes the second lowest (USD 2914.05). Maintenance cost of the house with other wall types (other than mud concrete walls) rage between USD 3966.89 – USD 9581.52. This can be regarded as an advantage for the 3D printed concrete walls.

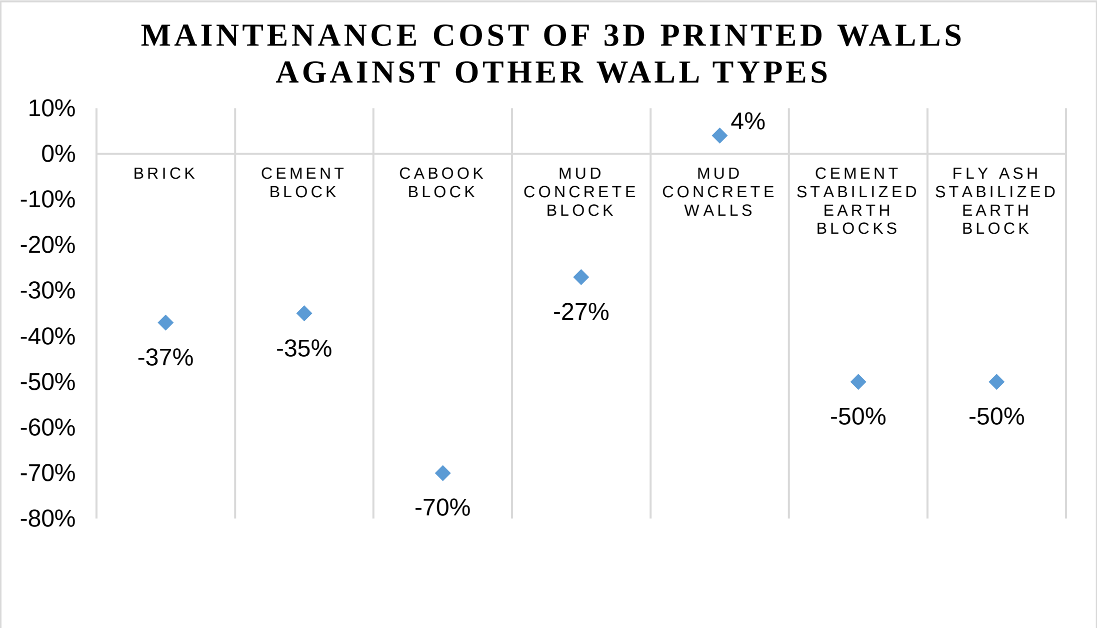

Figure 5.6: Maintenance cost of 3D printed concrete walls against other wall types

As depicted in Figure 5.6, 3D printed wall save maintenance cost by 70% compared to Cabook block which is the highest percentage saving. Maintenance cost saving against Bricks and Cement Blocks which are frequently used in Sri Lankan housing construction are 37% and 35% respectively. Maintenance cost of 3D printed concrete walls is slightly high (4%) compared only to mud concrete walls. The possible reasons for this saving in the maintenance cost would be high durability associated with concrete walls and elimination of the plastering works which requires maintenance.

5.6 Comparison of Energy Cost

Another main cost component to be considered in life cycle cost calculations in housing projects is Energy Cost.

Table 5.3 and Figure 5.7 compares the energy cost of model house with 3D printed concrete walls and with other wall types used in housing construction. Accordingly, 3D printed concrete walls incur the lowest energy cost which is USD 13,665.60 whereas other walling types incur USD 15,710.90 – USD 23,569.68 for the considered model house. This adds another plus point to the 3D printed concrete walls over the other types used in housing construction.

Table 5.3: Comparison of energy cost of model house with 3D printed concrete walls vs. other wall types

Walling Material	**Energy Cost of Houses USD (2017 prices)**	**Reference**
Bricks	18,799.49	(Udawatta, 2018)
Cement Blocks	20,539.55	
Cabook Block	23,569.68	
Mud concrete block	19,444.52	
Mud concrete walls	15,710.90	
Cement Stabilized Earth Blocks	19,924.54	
Fly ash stabilized earth block	21,939.13	
3D printed concrete walls	**13,665.60**	

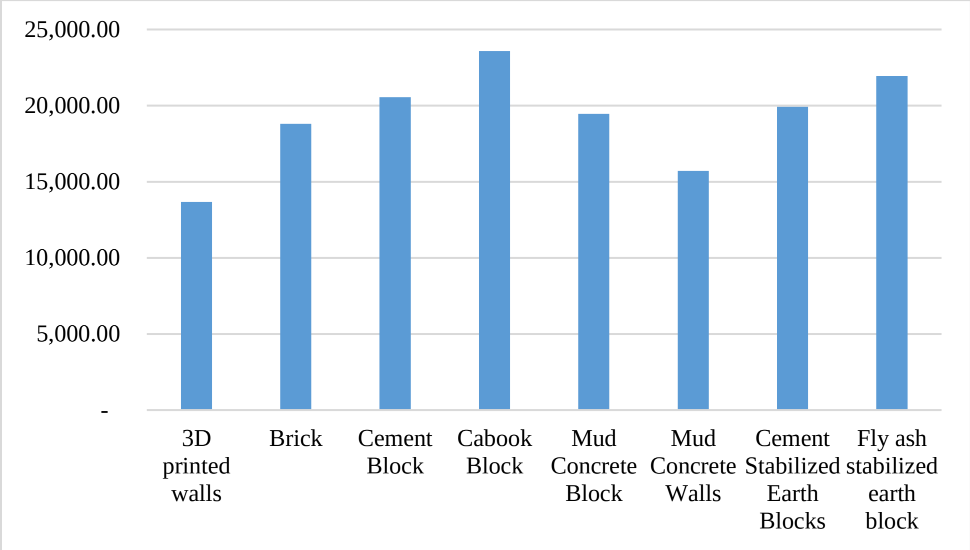

Figure 5.7: Comparison of energy cost of model house with 3D printed concrete walls vs. other wall types

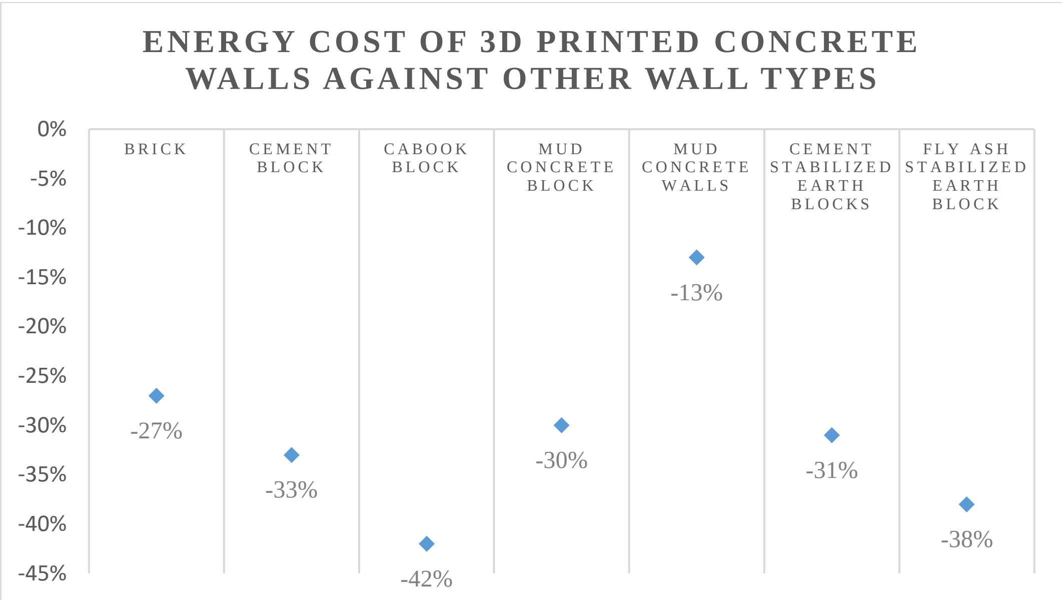

Figure 5.8: Energy cost of 3D printed concrete walls against other wall types

Figure 5.8 further graphically illustrate the saving of energy cost possible through the usage of 3D printed concrete walls instead of other walling options in housing construction. The graph indicates the highest energy cost saving against Cabook block (42%). It further shows 27% and 33% energy cost savings possible through opting 3D printed concrete walls instead of brick walls and Cement Block walls respectively which are the mostly used walling material in Sri Lankan housing construction sector.

The possible reason would be that the 3D printed concrete walls with internal cavities have significantly low energy gain that requires to be disposed by air conditioners. The lower U-value of the 3D printed concrete walls can also be the underlying reason that causes the lower energy gain.

5.7 Comparison of Resale Value

Resale value here denotes the amount of money expected by selling the debris at the end of the lifetime of the house. Accordingly, higher the resale value, lower the lifecycle cost. Resale value of 3D printed concrete walls after 60 years of age was calculated as described in section 4.7, assuming 90% of the volume is used as aggregate base course (Cadenazzi, et al., 2019). Resale value of other elements of the model house were obtained from the data published by Udawatta (2018).

Resale value of the model house with 3D printed concrete walls and with other types of walls are indicated in table 5.4 and Figure 5.9. Accordingly, model house with 3D printed concrete walls has the second lowest resale value. Even though 90% of its volume can be resold, the value generated is less when used as road pavement. Fly ash stabilized earth block has the highest resale value whereas the lowest resale value resulted by using Cement Stabilized Earth Blocks.

Table 5.4: Comparison of resale value of model house with 3D printed concrete walls vs. other wall types

Walling Material	Resale Value of Houses USD (2017 prices)	Reference
Bricks	2,940.34	(Udawatta, 2018)
Cement Blocks	2,306.25	
Cabook Block	2000.65	
Mud concrete block	2169.16	
Mud concrete walls	2184.4	
Cement Stabilized Earth Blocks	1200.55	
Fly ash stabilized earth block	3828.28	
3D printed concrete walls	**1656.55**	

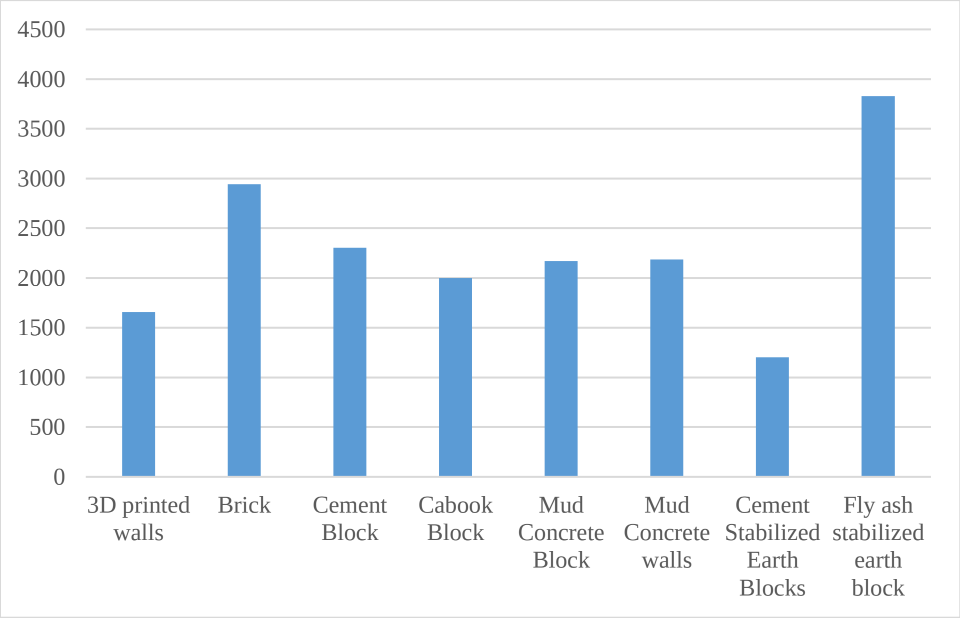

Figure 5.9: Comparison of Resale value of model house with 3D printed concrete walls vs. other wall types

Figure 5.10 illustrate the percentage resale value of 3D printed concrete walls against the other walling types used in housing construction sector. Accordingly, resale value of 3D printed concrete walls are 38% higher than the Cement Stabilized Earth Blocks whereas it is 17% - 57% lower than all other wall material types. Further, the resale value of 3D printed concrete walls are 44% and 28% lesser than brick walls and Cement Block walls which are the most frequently used building material in housing construction sector. Consequently, this figure of resale value weakly contributes to decrease the lifecycle cost of the 3D printed concrete walls.

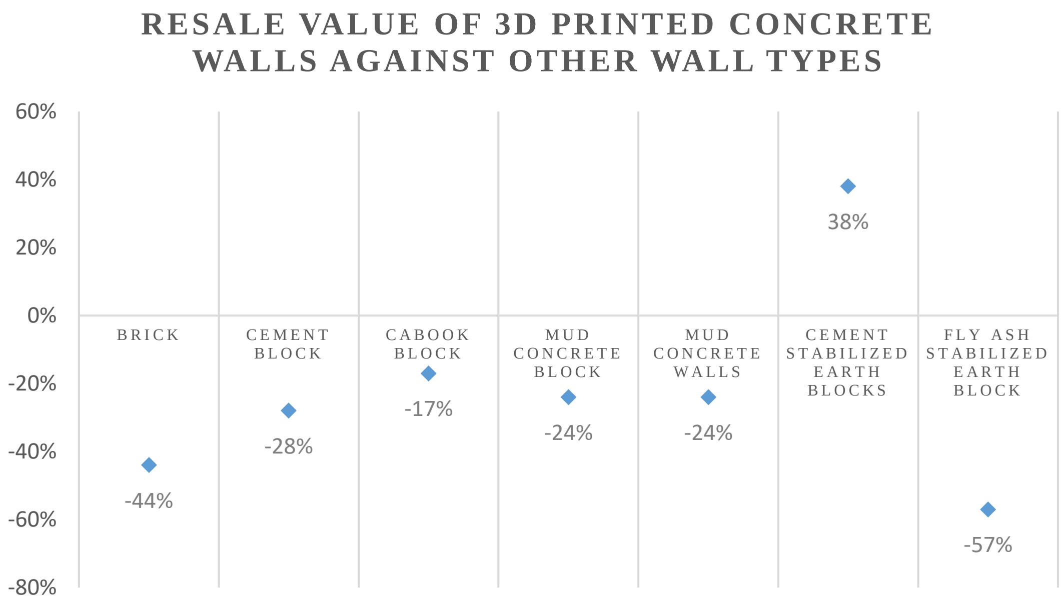

Figure 5.10: Resale value of 3D printed concrete walls against other wall types

5.8 Comparison of Life Cycle Cost

Life cycle cost calculation combines the above discussed cost aspects in order to analyse the economic sustainability of the walling solutions.

Table 5.5 and Figure 5.11 indicate the lifecycle cost of the considered model house with 3D printed concrete walls and with other types of walls.

Table 5.5: Comparison of life cycle cost of model house with 3D printed concrete walls vs. other wall types

Walling Material	Life Cycle Cost of Houses USD (2017 prices)	Reference
Bricks	28,412.40	(Udawatta, 2018)
Cement Blocks	28,465.38	
Cabook Block	36,803.24	
Mud concrete block	26,591.82	
Mud concrete walls	20,560.20	
Cement Stabilized Earth Blocks	31,811.96	
Fly ash stabilized earth block	31,310.38	
3D printed concrete walls	**25,120.23**	

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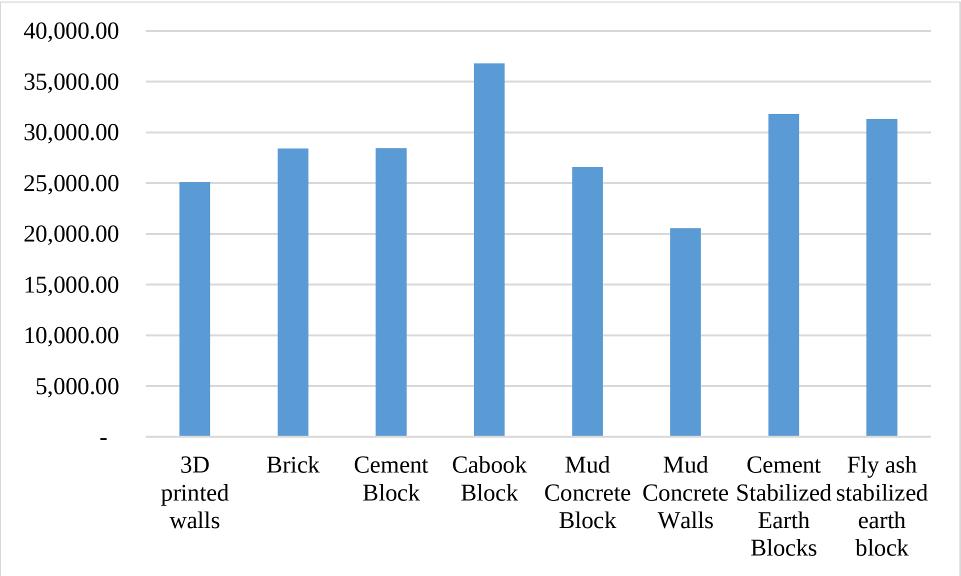

Figure 5.11: Comparison of Life cycle cost of model house with 3D printed concrete walls vs. other wall types

As indicated by Table 5.5 and Figure 5.11, the lower energy gain and maintenance costs of 3D printed concrete walls has offset the higher initial cost, overheads and lower resale value resulting the second lowest lifecycle cost (USD 25,104.23). It denotes that the 3D printed concrete walls is more economically sustainable walling solution for housing construction in Sri Lanka.

Model house with Mud concrete walls has yielded the lowest lifecycle cost (USD 20,560.20) while frequently used Brick walls and Cement block walls have yielded lifecycle costs of USD 28,412.40 and USD 28,465.38 respectively for the considered model house.

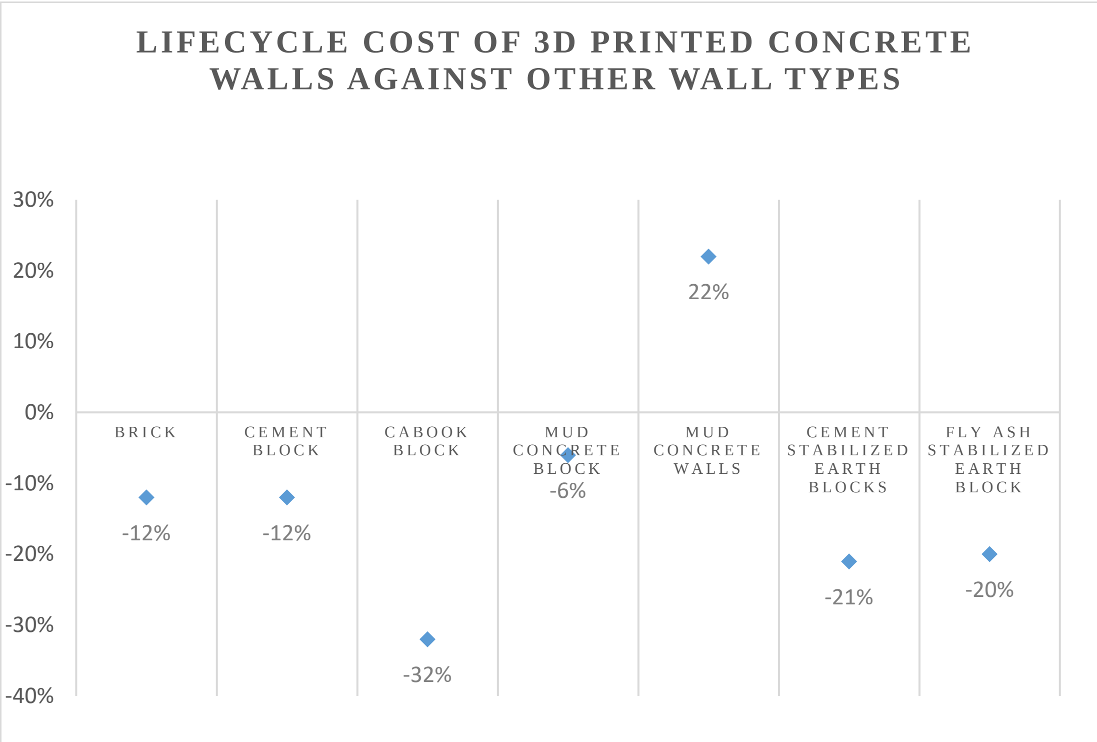

Figure 5.12: Life cycle cost of 3D printed concrete walls vs. other wall types

Lifecycle cost saving in other words, economic sustainability of 3D printed concrete walls compared to other walling types used in housing construction are illustrated in figure 5.12. Accordingly, 3D printed concrete walls are 6% economically sustainable than Mud Concrete Blocks which is the best solution in terms of economic sustainability after the 3D printed concrete walls while 12% economically sustainable than Brick walls and Cement Block walls which are the commonly used building materials in the Sri Lankan Construction industry at the present. The economic sustainability of 3D walls against Cabook Blocks is 32% which is the least economically sustainable walling solution. However, 3D printed concrete walls are 22% environmentally unsustainable compared to Mud Concrete walls.

The components of the life cycle cost of 3D printed house can be shown in figure 5.13.

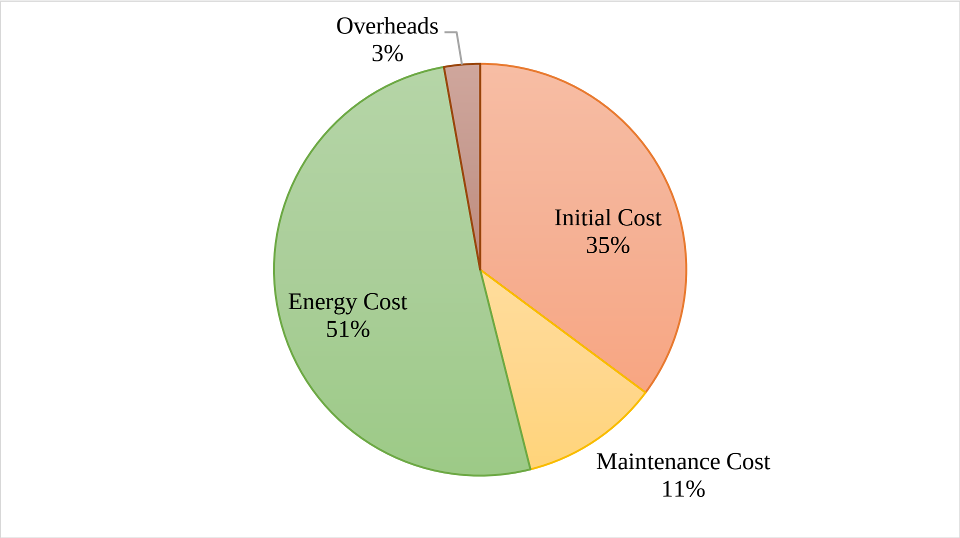

Figure 5.13: Contribution of different components of LCC 3D Printed model house

The energy cost having 51% contribution, is the main cost component in Life Cycle Cost of 3D printed building. Initial cost bears 35% contribution and maintenance cost bears 11% contribution for the LCC of 3D printed concrete walls.

5.9 Embodied Energy Analysis

As per the research calculations, the embodied energy of the 100 square feet of 3D printed wall is 4,297.166 MJ (See Annexure – 4). The embodied energy comparison of 100 sqft of the 3D printed concrete walls with other wall types are shown in figure 5.14.

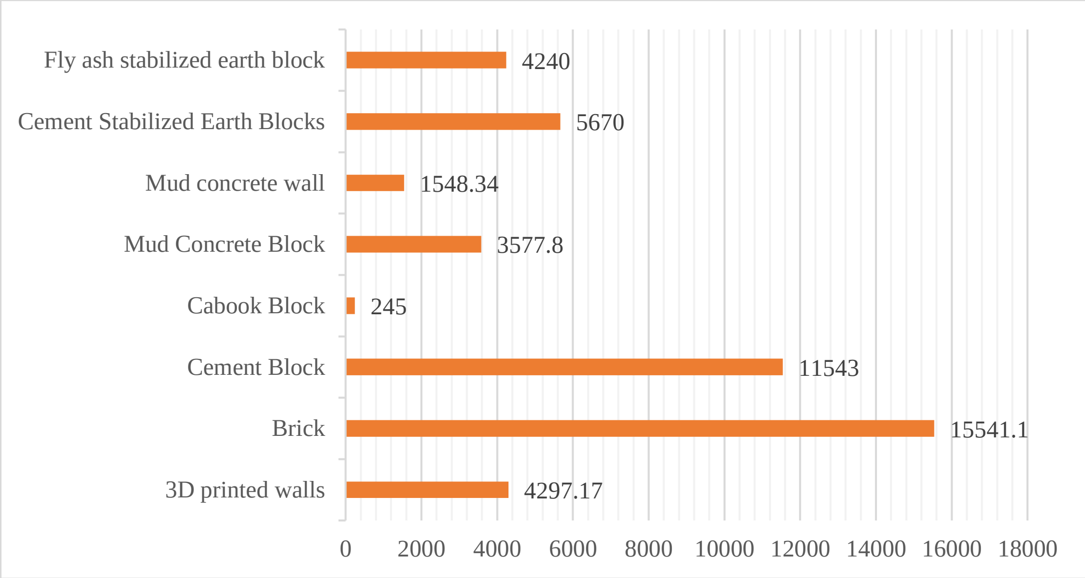

Figure 5.14: Comparison of the Embodied Energy.

As shown in Figure 5.14, Cabook wall has the lowest Embodied Energy whereas Brick wall has the highest. Embodied Energy of 3D printed concrete walls are lesser than Brick walls and Cement Block walls which are the common walling materials in Sri Lanka.

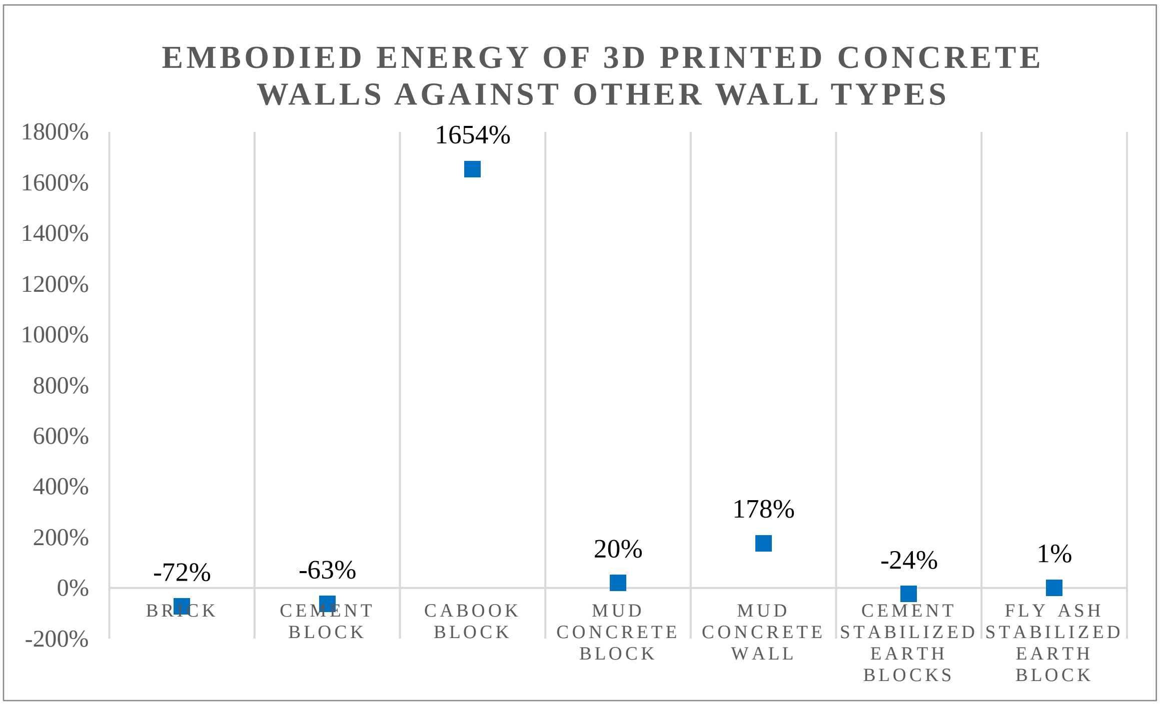

Figure 5.15: Embodied Energy comparison of 3D printed concrete walls vs. other wall types

As indicated in figure 5.15, 3D printed concrete walls saves energy in production by 72% and 63% compared to Brick and Cement Block walls respectively. It denotes that 3D printed concrete walls are much environmentally sustainable than the commonly used walling materials in housing sector. However, 3D printed concrete walls are remarkably unsustainable (1654%) in environmental aspects compared to Cabook walling solution.

The process wise breakdown of the embodied energy in 3D printed concrete walls is shown in Figure 5.15.

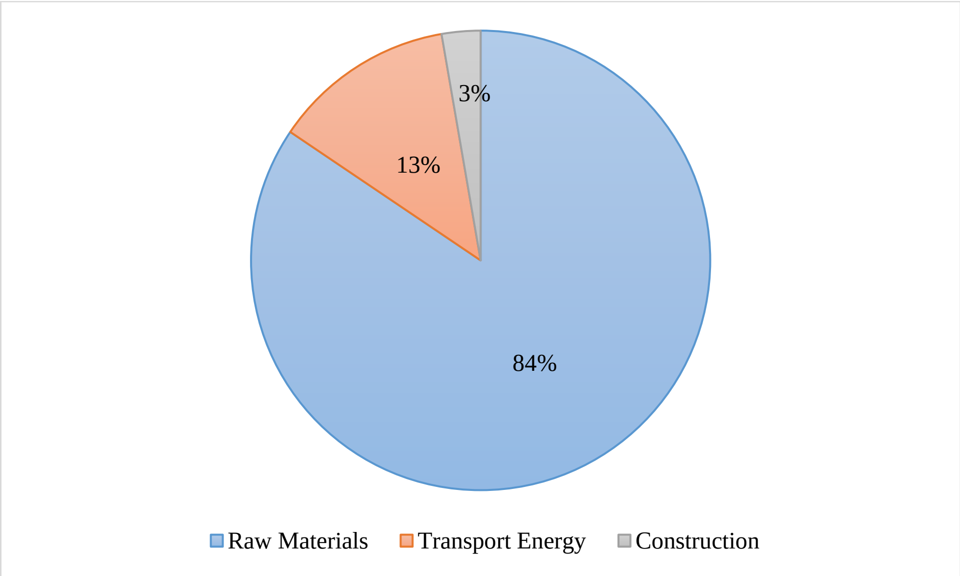

Figure 5.16: Embodied Energy Breakdown of 3D printed concrete walls based on process

As indicated in the figure, energy used to produce fiber cement concrete represent majority (84%) of the total embodied energy in 3D printed concrete walls. While energy required in transportation of raw materials, machines etc. contributes to 13% of the total energy, the energy requirement in printing process represents only 3%.

As further analysed in figure 5.16, majority (78%) of the fuel used in the process is fossil fuel which would add a negative point in terms of environmental sustainability dimensions. Electricity contributes only 14% of the total energy consumptions in 3D printed wall construction.

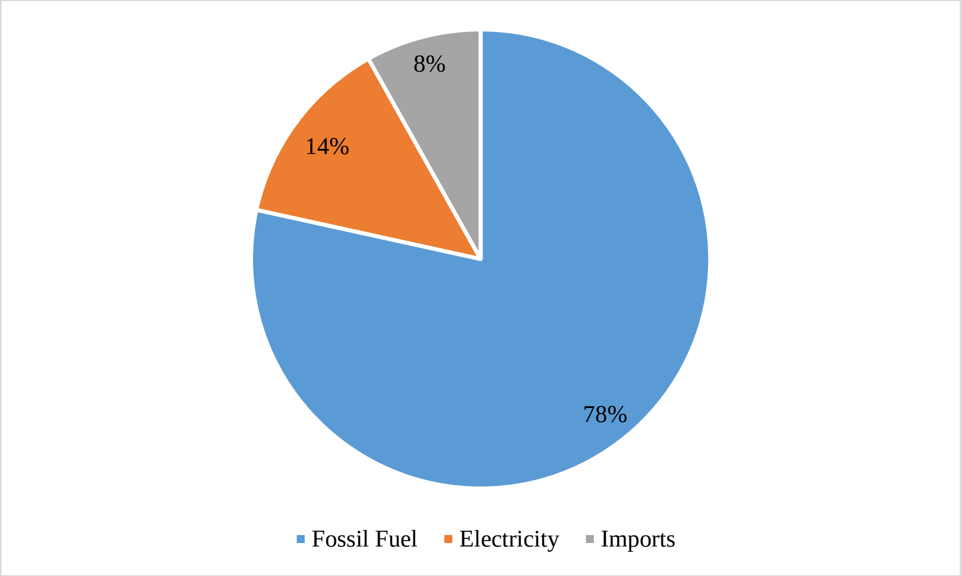

Figure 5.17: Embodied Energy Breakdown based on fuel type

5.10 Embodied Carbon Analysis

As resulted from the calculations, total Embodied Carbon of 3D printed wall is 85kg per 100 sqft of wall area. Calculation of the carbon footprint is annexed in Annexure – 4.

Figure 5.17 shows the breakdown of the carbon contribution according to the fuel type.

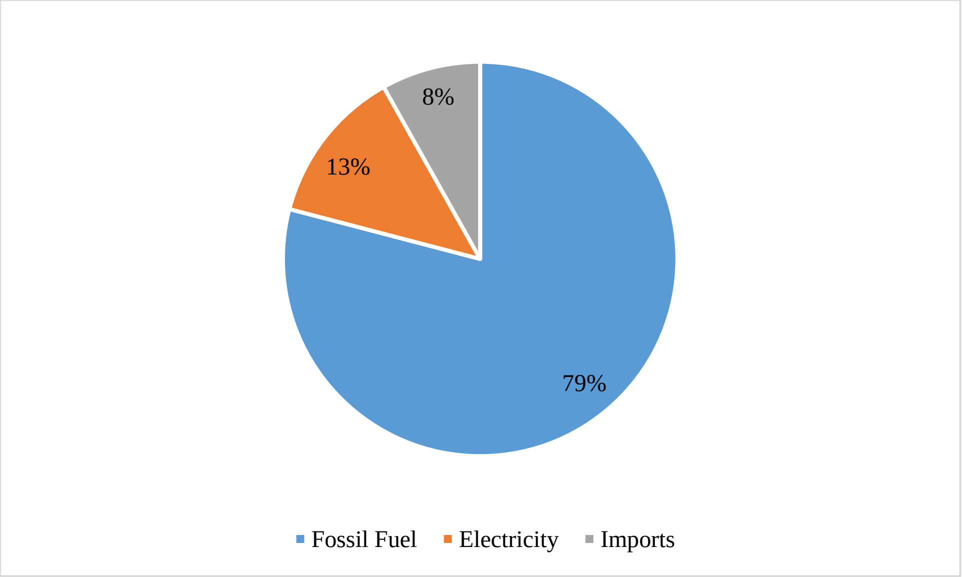

Figure 5.18: Embodied carbon based on the fuel type

It indicates that the highest carbon contribution (80%) is occurred in the construction of 3D printed concrete walls through fossil fuel while electricity contributes to 12% of the total embodied carbon.

5.11 Overall Sustainability of 3D printed concrete walls

Figure 5.18 combines the graphs presented under Figure 5.12 and Figure 5.15 to illustrate the Life Cycle Cost and Embodied Energy of 3D printed concrete walls against other walling options.

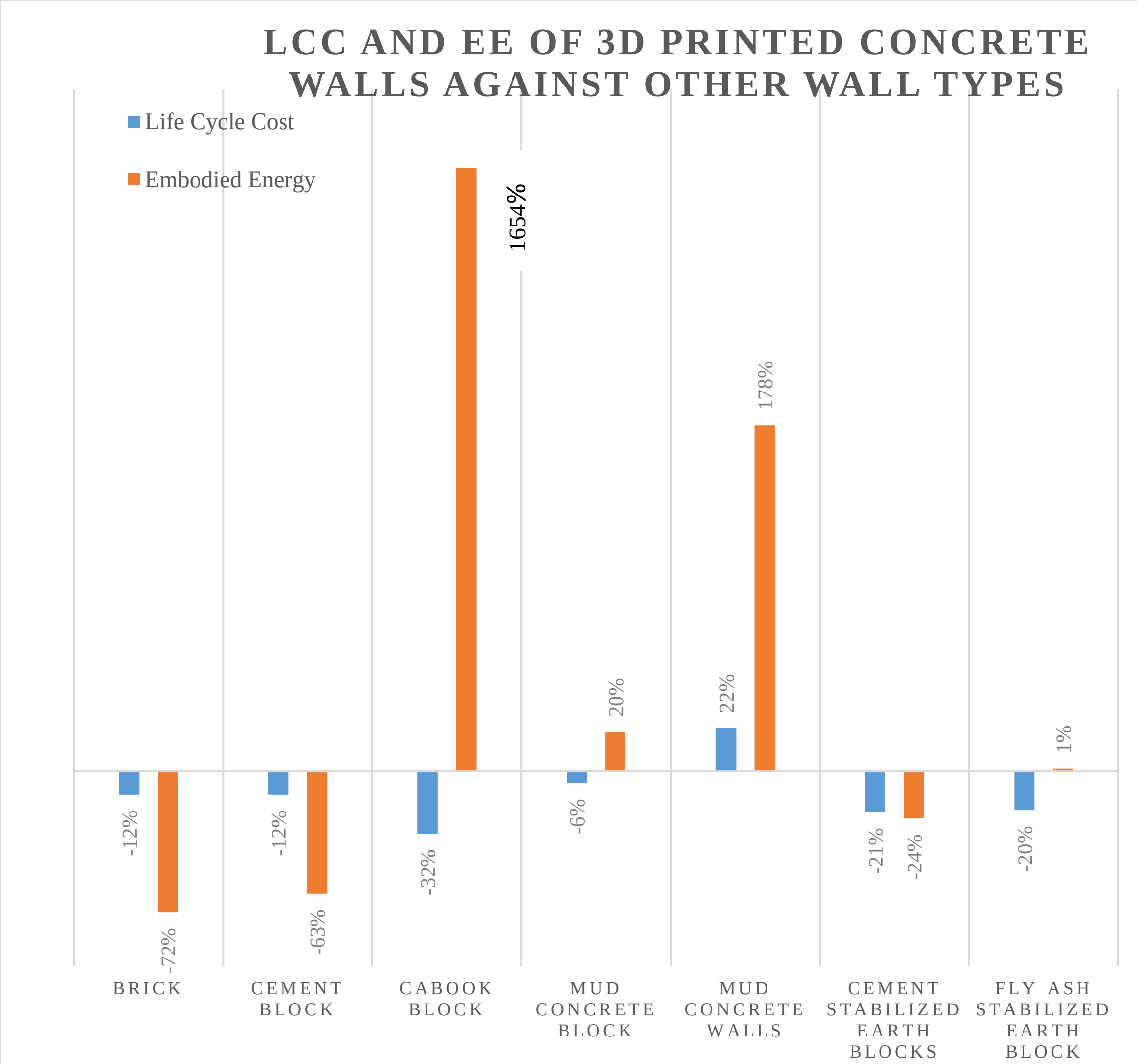

Figure 5.19: Life cycle cost and Embodied Energy of 3D printed concrete walls vs. other wall types

As shown in the graph, both Lifecycle Cost and Embodied Energy of 3D printed concrete wall are lesser than Brick walls, Cement Block walls and Cement Stabilized Earth Block Walls. That means, 3D printed wall is both economically and environmentally sustainable compared to the mentioned three wall types in the Sri Lankan housing sector.

Moreover, the Lifecycle Cost of 3D printed concrete wall is negative whereas Embodied Energy is positive against Cabook Block walls, Mud Concrete Block walls and Fly Ash Stabilized Earth Block walls. It denotes that 3D printed wall is economically sustainable but environmentally unsustainable in comparison with the said walling solutions. Further, compared to Cabook block walls, 3D printed wall is environmentally unsustainable at a remarkable rate.

However, 3D printed wall is both economically and environmentally unsustainable compared to Mud Concrete walls. The graph indicates positive Lifecycle Cost and Embodied energy of 3D printed wall against Mud Concrete walls. Moreover, with Mud concrete walls, environmental performance of 3D printed concrete walls is poorer compared to economic performance.

5.12 Summary

3D printed wall is the second economically sustainable solution for the housing sector in Sri Lanka, with lowest maintenance cost and energy cost however with highest initial cost and low resale value. In terms of environmental sustainability, 3D printed concrete walls perform better compared to Brick walls, Cement Block walls and Cement Stabilized Earth Block Walls. In combination, 3D printed concrete walls are both economically and environmentally sustainable compared to the said three wall types among which the mostly used Brick and Block walls in the Sri Lankan housing construction is included.

CHAPTER 06 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions and Recommendations

"Shelter" which is one of the basic human needs, has become unaffordable at the present for several reasons. In response, people now a days has tended to use technology advancements to seek more sustainable solutions for the issue. 3D printing has been regarded as such a solution in the housing sector worldwide. Nevertheless, Sri Lankan housing sector is not yet ready to incorporate 3D printing technology. Therefore, direct insights on the sustainability dimensions of 3D printed concrete walls in comparison with other walling types which are already used and are with high potential to be used will effectively promote the introduction of 3D printing to the housing construction sector in Sri Lanka.

Before studying the matter in deep, the first attempt was to identify the technical aspects in 3D printing which are required to carry out the calculations. Even though it's not many years from the start of the frequent use in construction industry, the 3D printing technology has a wide range of usage. Based on such literature, the technical aspect of 3D printing including available technologies, methods, currently used materials and their thermal transmittance, printing process and equipment used were ascertained in order to proceed with the research study.

The calculations of this study were carried out based on the onsite printing mechanism. The printer that was assumed to be used on site was a gantry type printer which was commonly used in commercial construction. The print material that was used for the calculation of life cycle cost was published mix by Le, et al. (2011) which was consisting of cement, fly ash, silica fume, sand, water, superplasticizers and fibre as reinforcement. However, for the purpose calculating the energy cost U value of the cork concrete mix was used due to the availability of data and similarity with the mixes published by Le, et al. (2011). Further, the above assumption was done in order to come up with a real-world scenario which includes an actual print shape by a 3D printer.

Having decided the technical details to be used in the study, the next attempt was to identify and choose the sustainability indicators for the study. Since the initial cost along could not give the full picture of a building element through the lifetime of the 3D printed elements, a Life Cycle Cost analysis was carried out. To ascertain the environmental sustainability aspects of the 3D printed elements Embodied Energy analysis was selected as the main measure since the limitation with comparable data on Carbon Footprint.

It was identified that the life cycle cost of the model house with 3D printed wall is the second lowest in compasrion with the other wall types, where Mud Concrete Walls has the least. Subsequently, 3D printed buildings become a better investment over the other wall types frequently used in Sri Lanka. Even though one may be misled by its high initial cost at a glance, the maintenance cost and the energy costs are considerably lower, which even offsets the higher initial cost of construction. Therefore, in addition to the advantages of the 3D printed wall identified in initial chapters, the cost benefits can be confirmed theoretically.

Therefore, 3D printing shows a great potential of implementing in Sri Lanka, when its cost advantages are bundled together with other advantages such as ability to print in any shape that can never be casted though traditional concrete laying methods, while cost of printing is irrespective of its shape of printing enabling advanced architectural features, less labour intensiveness and less time consumption.

The environmental aspects evaluated through the embodied energy analysis showed the 3D printed concrete walls are environmentlly frendlier than the frequenly used brick and block work which is also a great advantage for a cost effective solution. However, the results of the study showed that the 3D printed concrete walls are having a considerably high embodied energy campared to Cabook walls and mud concrete walls. Furter, embodied carbon analysis revealed that the highest carbon contribution in the process is through fossil fuel which certainly provides food for thought.

In essence, when compared to the Brick and Cement Block walls which are the two dominant walling types in the Sri Lankan housing sector, 3D printed wall is both economically and environmentally sustainable. This finding bundled together with the so-called advantages inevitably prooves a higher potential of 3D printed concrete walls to be incorporated in Sri Lanken housing construction industry. Further, this research results provides clear guidance on the level of economic and environmental sustainbility possible by choosing 3D printed concrete wall over other potential walling types in Sri Lankan housing sector namely Cabook block, Mud Concrete Block, Mud Concrete Walls, Cement Stabilized Earth Block and Fly Ash Stabilized Earth Block walls. It is recommended to use these research findings in combination with the studies on the technical aspects of the walling solutions such as strength, moss growth, surface erosion, fire resistance etc. in deciding a wall type in a given scenario.

6.2 Limitations of the Research

Secondary data published in the literature were used in this research since still 3D printing has never been used in the Sri Lankan construction industry. The analsysis is based on certain assumptions and data from previous researches to make the results of this research comparable to such previous research results. Further, environmental sustainability was decided based on Embodied Energy due to the limitation of comparable data in the previous researches on other indicators.

6.3 Further Research

- The analsysis is based on certain assumptions and data obtained from literature. Therefore, it can be recommended that further reseaches to be carried out with small scale real samples of 3D printed concrete elements

- Compared to the traditionally concrete mixing and laying process, the 3D printed concrete would be significantly economical due to the elimination of reinforcement and formwork. Hence, 3D printing would be economical not only for the residential construction but also for the large scale construction projects. Therefore, research can be extended for large scale construction projects.

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ANNEXURES

PRINTER COST CALCULATION **ANNEXURE - 1**

Price Breakdown of 3D Printer rate per houses of 500 sqft
EURO to LKR = 172 LKR (2017 June)

	Desciption	Qty	Unit	Rate in EURO	Rate in LKR	Factor	Amount	Remarks
	Printer Modules Height = 2 modules of 2.5 m, Length = 3 modules of 2.5 m Width = 3 modules of 2.5 m	1	nr	246,000.00	42,312,000.00	0.00100	42,312.00	Assume Modules can print approx. 1,000 houses before replacement.
	Printer Price excl. taxes and transport including nozzles and slicing software	1	nr	257,000.00	44,204,000.00	0.00100	44,204.00	Assume Printer can print approx. 1,000 houses before replacement
	Print head	1	nr	24	4,128.00	0.10000	412.80	Assume print head can be used for 10 houses
	Mixer pumps, weight control, 20 m hose	1	nr	32	5,504.00	0.00100	5.50	Assume mixer pumps, weight controls and hose can be used for 1000 houses
	Silo 4m3	1	nr	18	3,096.00	0.00100	3.10	Assume mixer pumps, weight controls and hose can be used for 1000 houses
	Insurance and freight charges (40 feet container) from Denmark to Sri Lanka	1	nr	2750	473,000.00	0.00100	473.00	Assume Printer can print approx. 1,000 houses before replacement.
	SL custom charges (5% PAL)	5%			87,001,728.00	0.00100	4,350.00	As per the custom tarrif charges HS CODE 8479.10.00 and tariff calculator.
	Concrete blocks for mounting	16	nr		110,000.00	0.00100	1,760.00	Assume 4nr, 1 m x 1 m x 1 m concrete blocks
	Electricity charges - Printer	374	KWh		22.85		8,545.90	17 hrs printing time for 500 sqft house, 22kW per hour
	Electricity charges - Mixer	172.55	KWh		22.85		3,942.77	17 hrs printing time for 500 sqft house, ref. 10.15 kW per hour
	Training cost	4	Weeks	6.00	1,032.00		4,128.00	Assume traning period as 1 month.
a	**Total of above costs**						**110,137.07**	
b	**Maintenace of Equipment, Cleaning, Storage Costs etc. - 10% of above**						**11,013.71**	
c	**Total cost of 3D Printer per house**						**121,150.77**	
	Say						**121,200.00**	
	In USD (2017 - 1 USD = 150 LKR)						**808.00**	

COST CALCULATION OF 3D PRINTED WALLS OF 500 SQFT BUILDING

ANNEXURE - 2

100 Days Hundred and Fifty Thousand Housing Project

Total volume of Concrete 19 m3 18.98

Below prices are without VAT prices

Description	Qty	Unit	Rate	Amount	Remarks
Materials					
Cement	11,001	Kg	16.70	183,716.70	LKR 835 per bag
Silica Fume	1,577	kg	300.00	473,100.00	2 USD per kg; Alibaba.com; 1 USD = 150 LKR
Sand	23,579	kg	2.60	61,305.40	Density = 1650 kg/m3
Fly ash	3,135	kg	6.00	18,810.00	LKR 5500 per ton
Polypropylene Fibre	23	Kg	210.00	4,788.00	1400 USD per ton; ECO Spindles
Superplasticizer	314	Kg	300.00	94,050.00	2 USD per kg; Alibaba.com; 1 USD = 150 LKR
Water	4,104	Kg		Electricity cost only	
Total of above				741,720.10	
Wastage - 2%				14,834.00	
Total of Materials				**756,554.10**	
Equipment					
3D Printer including electricity cost		Item		121,200.00	Ref. Printer cost breakdown
Forklift for assembly and disassembly	1.5	Days	16,000.00	24,000.00	
Electricity Charges - Water pump	0.11	KWh	22.85	2.51	
Truck for moving parts	1	Trip	8,000.00	8,000.00	Assume 20 km; Assume 3 ton truck
Total Equipment Cost				**153,202.51**	
Labour					
Assembly - Technicians	24	hours	400	9,600.00	3 Technicians for 8 hours
Disassembly - Technicians	12	hours	400	4,800.00	2 Technicians for 8 hours
Operators	16	hours	400	6,400.00	2 Operators for 8 hours
Total Labour Cost				**20,800.00**	
Total wall cost of 3D printed house in LKR				**930,556.61**	
Rate per m3 of concrete				**48,977.00**	326.51
Total wall cost of 3D printed house in USD (2017 - 1 USD = 150 LKR)				**6,204.00**	

LIFE CYCLE COST CALCULATION

ANNEXURE - 3

Element	Life Span	Initial Cost ($)	Mainteance Cost ($)	Resale value ($)	Reference
Foundation	<60 years	390.33	0.00	390.33	(Udawatta, 2018)
Walls (1460 sqft)	>60 years	6204.00	0.00	456.00	Refer cost calculation
Front Concrete Columns	>60 years	70.00	0.00	0.00	(Udawatta, 2018)
Roof Work	35 years	955.04	64.59	744.93	(Udawatta, 2018)
Doors and Windows	>60 years	426.00	0.00	63.90	(Udawatta, 2018)
Floor concrete	>60 years	587.16	0.00	0.00	(Udawatta, 2018)
Bathroom	30 years	40.00	3.98	1.39	(Udawatta, 2018)
Electrical	50 years	126.67	2.70	0.00	(Udawatta, 2018)
Internal wall plastering		0.00	0.00	0.00	Plastering not required
External wall plastering		0.00	0.00	0.00	Plastering not required
Internal painting	6 years	337.33	1913.19	0.00	(Udawatta, 2018)
External painting	6 years	161.33	915.01	0.00	(Udawatta, 2018)
Septic tank	30 years	146.67	14.58	0.00	(Udawatta, 2018)
Total of above costs		**9444.53**	**2914.05**	**1656.55**	

<u>Summary</u>

Initial Cost	$	9,444.53
Maintenance Cost	$	2,914.05
Resale value	$	1,656.55
Energy Cost	$	13,665.60
Overheads	$	752.60
Life Cycle Cost	$	25,120.23

EMBODIED ENERGY AND EMBODIED CARBON CALCULATION

ANNEXURE - 4

Material requirement for 10' x 10' 3D Printed Wall

Total Mortar Requirement	1.30	m3

Material requirement	Cement(kg)	Silica Fume (kg)	Sand(kg)	Flyash(kg)	Polypropylene Fibre (kg)	Water (kg)	Superplasticizer
	752.70	107.90	1613.30	214.50	1.56	301.6	21.45

Transport Distance (Km)

	Cement	Silica Fume	Sand	Flyash	Polypropylene Fibre	Water (kg)	Superplasticizer	Printer	Printer
Distance	152	25	257	174	25	0	25	25	25
Method	Lorry	Lorry	Lorry	Lorry	Lorry	200 W, 125 L/Min water pump	Lorry	Freight	Lorry

Level 1: Raw Material Embodied Energy

	Qty	Unit	MJ Per Kg				MJ For 1.3 m3			
			Bio Mass	Fossil Fuel	Electricity	Imports	Bio Mass	Fossil Fuel	Electricity	Imports
Cement	752.70	Kg		3.681	0.601			2770.689	452.373	
Silica Fume	107.90	Kg				0.036				3.884
Sand	1613.30	Kg								
Flyash	214.50	Kg		0.100				21.450		
Polypropylene Fibre	1.56	Kg				95.400				148.824
Water	301.6	Kg			0.096				28.9536	
Superplasticizer	21.45	Kg				9.000				193.05
Total							0.000	2792.139	481.3266	345.758

Level 2: Transport of Raw Material / Equipment

	Qty (Kg)	Unit	MJ Per Kg				MJ For 1.3 m3			
			Bio Mass	Fossil Fuel	Electricity		Bio Mass	Fossil Fuel	Electricity	
Cement	752.7	Kg		0.071				53.442		
Silica Fume	107.90	Kg		0.029				3.129		
Sand	1613.30	Kg		0.120				193.596		
Flyash	214.50	Kg		0.203				43.544		
Polypropylene Fibre	1.56	Kg		0.029				0.045		
Water	301.60	Kg								
Superplasticizer	21.45	Kg		0.029				0.622		
Printer / Mixer etc. (Shipping)	Assume 1 Ton							0.749		
Printer / Mixer etc. (Inland Transporting)	Assume 1 Ton							7.804		
Printer / Mixer etc. (Loading & Unloading using Forklift)	Assume 1 Ton							243.489		
Total								546.420		

Level 3: Mixing, Pumping and Printing of 3D printed walls

	Qty (Kg)	Unit	Per Kg				MJ for 1.30 m3			
			Bio Mass	Fossil Fuel	Electricity		Bio Mass	Fossil Fuel	Electricity	
Mixing									41.523	
Printing									90	
Total									131.523	

Summary

Energy By Stage		
Embodied Energy in Raw Materials	3619.224	MJ
Transport Energy for Raw Materials and Finished Products	546.420	MJ
Energy in Construction	131.523	MJ
	4297.166	MJ

Energy By Fuel			CO2 Emission Rate (Kg/C/MJ)	Carbon Emission (Kg)	
Bio mass	0.000	MJ	0.015	0.000	
Fossil Fuel	3338.559	MJ	0.020	67.773	
Electricity	612.8496	MJ	0.018	11.252	(Dias & Pooliyadda, 2004)
Imports	345.758	MJ	0.020	6.915	(Dias & Pooliyadda, 2004)
				85.940	