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Environmental Footprint and Economics of a Full-Scale 3D-Printed House

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Abstract: 3D printing, is a newly adopted technique in the construction sector with the aim to improve the economics and alleviate environmental impacts. This study assesses the eco-efficiency of 3D printing compared to conventional construction methods in large-scale structural fabrication. A single-storey 3D-printed house was selected in the United Arab Emirates to conduct the comparative assessment against traditional concrete construction. The life cycle assessment (LCA) framework is utilized to quantify the environmental loads of raw materials extraction and manufacturing, as well as energy consumption during construction and operation phases. The economics of the selected structural systems were investigated through life cycle costing analysis (LCCA), that included mainly the construction costs and energy savings. An eco-efficiency analysis was employed to aggregate the results of the LCA and LCCA into a single framework to aid in decision making by selecting the optimum and most eco-efficient alternative. The findings revealed that houses built using additive manufacturing and 3D printed materials were more environmentally favourable. The conventional construction method had higher impacts when compared to the 3D printing method with global warming potential of 1154.20 and 608.55 kg CO_2 eq, non-carcinogenic toxicity 675.10 and 11.9 kg 1,4-DCB, and water consumption 233.35 and 183.95 m^3, respectively. The 3D printed house was also found to be an economically viable option, with 78% reduction in the overall capital costs when compared to conventional construction methods. The combined environmental and economic results revealed that the overall process of the 3D-printed house had higher eco efficiency compared to concrete-based construction. The main results of the sensitivity analysis revealed that up to 90% of the environmental impacts in 3D printing mortars can be mitigated with decreasing cement ratios.

Keywords: additive manufacturing; life cycle assessment; life cycle costing; sustainable construction; concrete

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1. Introduction

The construction sector is responsible for significant environmental stresses, consuming 48% of global supplied energy on an annual basis and depleting the natural resources [1]. In addition to exploitation of materials, manufacturing of construction materials and operational works are responsible for 38% of worldwide greenhouse gas emissions [2]. The sustainable development goals demand continuous monitoring of emissions and potential health risks of the implemented system. Understanding the environmental impacts of infrastructure and construction practices aids in developing efficient energy techniques. Moreover, low fatalities and injuries are common in the construction industry which encourages the automation of construction-related techniques. Furthermore, automation of construction activities is preferred to account for low productivity rates. More specifically, labour productivity, which is defined as construction workload expressed in units per man hour, plays a key role in the capital investment of the project as well as meeting the global housing demand [3]. Current rates of productivity combined with an increase in urbanization has been a concern in sustaining the increasing housing demand which is estimated to reach 230 billion m^2 in the next 40 years [4]. As a result, additive manufacturing has been proposed as an alternative to conventional construction. Additive manufacturing or 3D printing is being assessed as a potential solution to current methods of construction for energy reduction, automation of construction methods, mitigation of environmental impacts, and cost savings [2].

In addition to the consideration of materials, the construction industries face a continuous challenge of having to complete construction of the structures within the shortest time, while still having to maintain safety and work quality. Innovations in the construction industry have explored different techniques to account for the technical drawbacks and environmental impacts associated with conventional construction techniques. Automation of activities in the construction site have been proposed, particularly additive manufacturing or 3D printing technology, to improve construction practices [5]. The additive manufacturing process operates by continuously adding a layer-by-layer extrusion paste. It is also defined as a method of digitally fabricating materials via printers [6]. Each 3D printed layer is a 2D representation from the computer aided design (CAD) or building information modelling (BIM) model that is deposited to the printer [7]. Digital fabrication enables customization and assembly of complex designs. Attempts have been made to utilize 3D printing techniques in the construction industry and evaluate the sustainability and implications on the economic, environmental and social aspects [5]. A case study in China demonstrated the potential of large-scale 3D printing, whereby several houses approximately 200 m^2 have been built using high quality cement alongside glass fiber to enhance strength [8]. Another application represented the functionality of 3D printing by prefabricating the components of a 5 storey building and later assembled on site [9]. Wu et al. [7] asserted the importance of selecting appropriate material to attain the desired level of detailing and withstand the loading on the structure. A Complex design of a 12 m $\times$ 12 m $\times$ 12 m house with complex details has been successfully implemented using 3D printing [7]. The house was printed with glass reinforced plastic extrusion paste which was able to resist corrosion, aging and water seepage.

Digital fabrication foresees the potential of mitigating the environmental constraints and reducing the materials used in building sector [4]. Moreover, utilization of 3D printing technology in the construction industry can potentially lead to a reduction of energy supply and overall emissions up to 5% by 2025 in large scale projects (i.e., large filament size) [4]. The environmental performance of implementing additive manufacturing methods in the construction sector has been explored. Several studies investigated the environmental impacts of additive manufacturing in the construction industry using life cycle assessment (LCA) systematic framework. Sinka et al. [10] explored the environmental impacts of different 3D printing cement and gypsum binders. The results revealed that gypsum-based mixes had an overall reduction in GWP of 84% as a result of lower energy use. Other studies investigated the performance of different construction elements. Mrazović et al. [11] compared the environmental performance of conventional and 3D-printing of different metal building elements (such as steel frame and steel brackets). Additive manufacturing proved to be compatible for construction which achieved 40% lower environmental impact (compared to conventional manufacturing methods) [11]. Agustí-Juan et al. [12] utilized LCA to identify the viability of constructing walls with varying complexities using 3D printing compared to conventional construction techniques. The results revealed that complexity of structures did not increase the overall costs and the design of the structure was not responsible for environmental constraints as opposed to conventional building techniques. Moreover, the literature has been focused on studying the environmental impacts particularly, climate change potential and energy consumption as they have been reported to have the greatest effects [13]. The climate change impact of conventional walls was 75%, whereas the 3D-printed wall had negligible impact (2%). Climate change was reported to have significant environmental impacts as a result of the GHGs emissions during the material production, manufacturing, transport and construction phases [12]. Another case study assessed the environmental impacts from the materials production and operation of 3D-printed wall and roof structures [14]. Results highlighted the minimal impacts of operation of fabrication robots, while the mainstream energy consumption originates from material production. Mohammad et al. [15] also investigated the environmental performance of 3D printed walls compared to conventional reinforced concrete ones. The 3D concrete printing (3DCP) scenarios yielded lower emissions in terms of global warming potential and acidification potential. The study further combined conventional reinforcement with 3DCP, and the environmental impacts were still lower than conventional construction techniques.

All of the above mentioned studies only assessed the environmental impacts of different structural elements, on the other hand, Han et al. [16] developed a 3D model simulating a 3D-printed house. The emissions were calculated using equations from the literature. The findings of the study revealed that construction using 3D printing technology resulted in higher emissions when compared to cast in-situ conventional concrete. Moreover, the study attributed the high emissions to cement production processes. Another study compared the environmental impacts of 3D printing and conventionally built house [17]. The study utilized concrete and cob (a sustainable material) to run the analysis. The 3D printing technology acquired lower impacts compared to conventional concrete construction. In terms of materials, cob attained lower impacts, nevertheless, 3DCP binder consumed less energy. In terms of economic viability, a case study in the United Kingdom investigated the financial feasibility of 3D printed residential structures using life cycle costing analysis (LCCA). The findings of the study revealed savings up to 35% when compared to conventional houses due to lower material consumption and eliminated labour cost [18].

Conventional construction is responsible for significant environmental and safety risks which compels introduction of new efficient and feasible alternatives. Digital technologies, particularly 3D printing, have been successfully implemented in the field of construction. Evaluation of the systems encompasses quantification of environmental impacts using the standard LCA tool and economic value of building structures using conventional manufacturing methods versus 3D printed methods. The capital and energy costs incurred over the life cycle of the examined structural systems are estimated using life cycle costing analysis. An eco-efficiency analysis is used to combine the results of the LCA and LCC into a single framework to assist decision makers with the choice of the optimum construction method taking account the environmental and economic perspectives. A search of recent publications (Table 1) in this field showed that most of the studies focus primarily on developing the 3D printing mortar and utilizing sustainable materials. The literature lacks comprehensive and integrated environmental and economic assessment of large-scale 3D printed buildings. Since this technology is under development, more studies are needed to optimize the materials and methods used from both environmental and economic perspectives. This study aims to enrich the literature with comprehensive assessment of such a knowledge base which is essential to drive the shift towards digital fabrication construction. This study provides a comparative assessment of a 3D-printed structure compared to conventional concrete construction. The comparative assessment is applied on an actual single-storey house located in Dubai, United Arab Emirates (UAE).

Table 1. Summary of life cycle assessment-based studies in the construction sector.

References	Boundary	3D-Printed Unit	Stages	Impact Assessment Method	Software	Database	Functional Unit	Evaluated Impacts
[6]	-	Hypothetical house model	Material acquisition; construction Phase	Building Life-cycle Sustainability Impact Assessment Standard	-	Local data; Literature review	1 m^2 wall; 1 m^2 roof	Global warming potential; Acidification; Photochemical Pollution; Eutrophication
[10]	Cradle to gate	Cube Samples	Production	IPCC 2013 GWP100a	SimaPro 8	Ecoinvent 3; Previous studies	1 m^3 binder	Global warming potential
[15]	Cradle to gate	Wall structure	Production; Construction	TRACI	GaBi 9.2.1.68	GaBi 2020	1 m^2 external load-bearing wall	Global warming potential; Acidification potential; Eutrophication potential; Smog formation potential; Fossil fuel depletion
[17]	Cradle to Site	One-storey house	Raw materials; Transportation; Construction	ReCiPe Midpoint (H) v1.03	SimaPro 9.0.0.35	Ecoinvent v3.1; Literature; Local data	1 m^2 load-bearing wall	global warming; Stratospheric ozone depletion; Fine particulate matter formation; Marine eutrophication; Land use; Mineral resource scarcity; Water use
[11]	-	Metallic building components	Raw material processing; Manufacturing; Transportation	-	SimaPro	Local data	1 steel bracket	Energy consumption; Human health; Water source depletion; Abiotic depletion of fossil fuels
[12]	Cradle to gate	Wall Structure	Raw material extraction; Transport; Materials production; Robotic fabrication	Recipe Midpoint (H) v1.12	SimaPro 8	Ecoinvent v3.1	1 m^2 of wall	Climate change; Ozone depletion; Human toxicity; Terrestrial acidification; Freshwater eutrophication; Terrestrial ecotoxicity; Freshwater ecotoxicity; Water depletion; Metal depletion; Fossil depletion
[2]	Cradle to grave; Cradle to gate	Wall and roof structures	Materials production; Operation energy	Recipe Midpoint (H) V1.06	SimaPro 8	Ecoinvent v2.2	1 m^2 of wall and roof structures	Climate change; Ozone depletion; Human toxicity; Water depletion; Metal depletion; Fossil depletion

2. Methodology

In this section, the structural system components and configurations were discussed, followed by a description of the 3D printing technology utilized to construct the house understudy. Moreover, the standard methods of the environmental and financial life cycle analyses were presented.

2.1. Structural Systems

A single-storey detached house located in the UAE was selected as a case study. Figure 1 shows the plan and elevation layouts of the selected house with a net floor area of 90 m^2 and total height of 4.5 m. The proposed structural systems include (1) conventional construction method using cast in place concrete walls and flat slab with beams and columns, and (2) additive manufacturing using self-reinforced printable mortar. It should be noted that the construction time frame of the 3D printed house was approximately 2 weeks, whereas the conventionally built house was 4 months based on local engineering contractors. The timeframe excludes the HVAC, plumbing, and finishes works as they are similar in both houses.

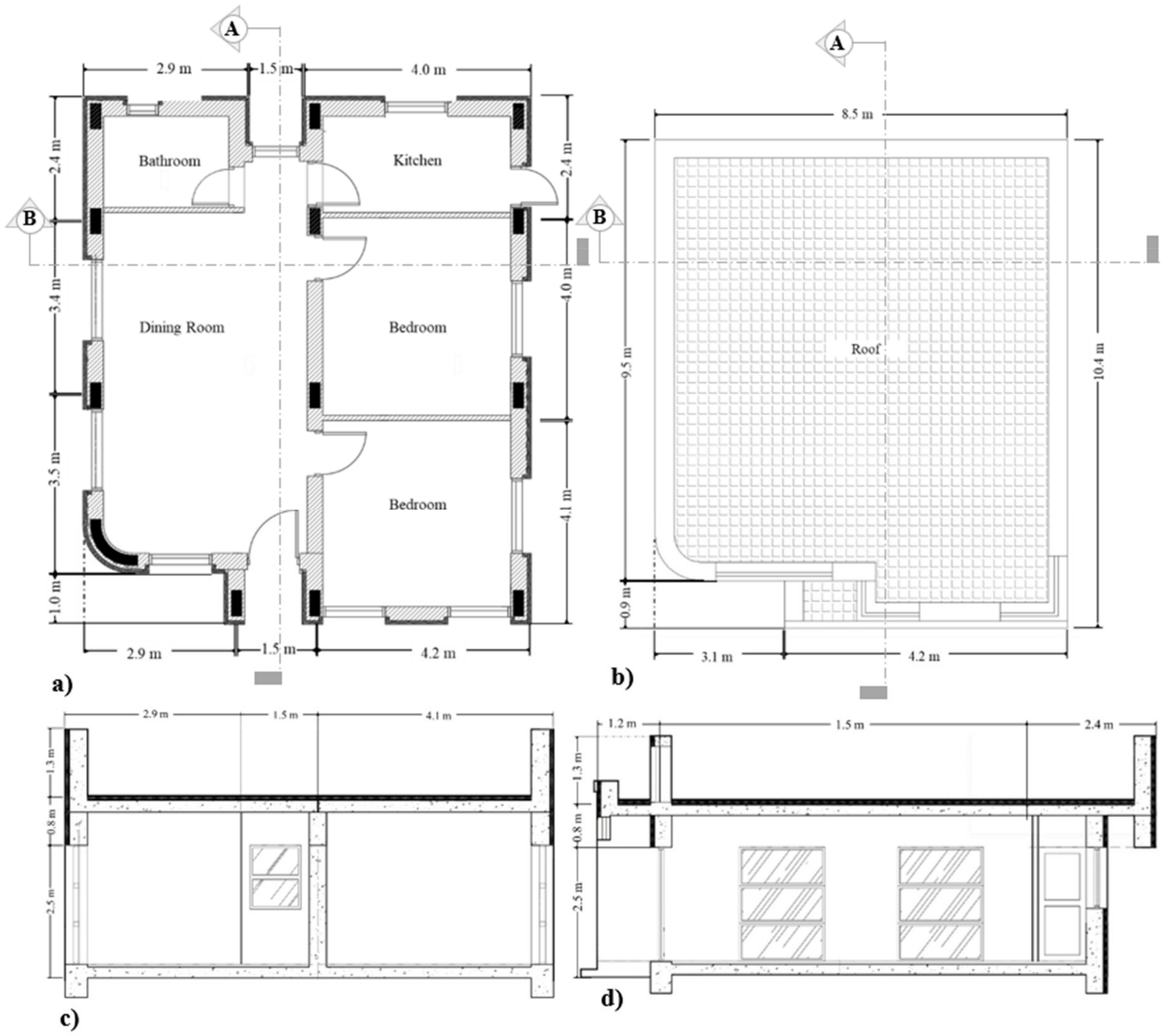

Figure 1. The technical drawings for (**a**) ground floor, (**b**) Site plan, (**c**) section A, and (**d**) section B.

Table 2 shows the details of the structural elements utilized for conventional concrete construction. The columns and beams have a cross-sectional area of 800 and 1600 cm^2, respectively, whereas the slab has a total area of 376 m^2. Wood formwork was utilized in construction of the columns, beams, and slabs of 3.8 m^2, 47 m^2, and 400 m^2, respectively.

There are 0.03, 0.04, and 0.245 m^3 of columns, beams, and slabs per m^2. The design of the steel reinforcement, confinement steel, and stirrups were conducted according to American Concrete Institute (ACI) standards [19]. Moreover, the considered primary loads in this study were the typical dead and live loads defined by American Society of Civil Engineers (ASCE) 7–10 [20].

Table 2. Dimensions and reinforcement of structural elements.

Element	Component		Value
External Wall	Specifications	Length (m) × Height (m) Required concrete (m^3) Total concrete bricks	37.8 × 2.95 6.19 15,478
Column	Specifications	Length (cm) × Width (cm) × Height (cm) Total number	40 × 20 × 295 13
	Reinforcement	Rebar size Spacing (cm) Total cross-sectional area (cm^2)	10 25 20.5
Beam	Specifications Reinforcement	Length (cm) × Width (cm) Rebar size Number of rebars Total cross-sectional area (cm^2)	40 × 40 22 6 23.22
Slab	Specifications	Slab depth (cm)	0.25
	Reinforcement *	Rebar size Spacing (cm) Total number of main reinforcements Total number of secondary reinforcements	10 20 78 95

* The design details include main and secondary reinforcing rebars.

The specifications and properties of the cementitious mortar used for conventional concrete and 3D printing mixtures are summarized in Table 3. The conventional concrete mix has cement, sand, and aggregates ratio of 1 to 1.5 to 1.3, respectively, while the cementitious 3D printing mortar consists of 70% sand and 30% binder (cement and additives) [21]. Moreover, the mix of the 3D printing mortar is characterized by low sulphate and chloride content which was designed for structural and non-structural elements.

Table 3. Properties of 3D printing and conventional construction materials *.

System	Components *	Specifications
Conventional Concrete **	Ultimate Compressive Strength (MPa) Water/cement Ratio Maximum Aggregate Size (mm) Slump (mm) Mixing Water (kg/m^3) Density Concrete (kg/m^3)Vt	35 0.5 20 20–80 200 2355
3D Printing Mortar *	Grain Size (mm) Initial Set (min) Final Set (min) Layer Thickness (mm) Ultimate Compressive Strength (MPa) Tensile Strength (N/mm^2) Flexural Strength (N/mm^2) Specific Heat Capacity (J/g·K) Air Void Content (%)	3 3 5 40 40 4 6 1.1 5.3

* Compiled from [21] and ** [22].

2.2. Additive Manufacturing Technology

The application of a large-scale 3D printed structure entails using an extrusion method, in which the structure was built by adding layers of the prepared mortar through a nozzle. The digital STL (STsereo Lithography) formatted file was converted into several 2D layers by means of CyBe CHYSEL software [21]. Moreover, Table 4 summarizes the input parameters required for the operation of the mobile 3D printer. Furthermore, the printing process was regulated through a control unit which operates the mixing system to pump the mortar through a hose into the robotic arm. The mortar was added layer by layer at the specified coordinates via a 40 mm nozzle. The 3D printing filaments were characterized by a zigzag pattern and the printed walls were hollow (39 cm).

Table 4. Operating parameters of the 3D printer used.

Parameter	Value
Print Speed (mm/s)	50–600
Travel speed (km/h)	3
Precision (mm)	1:1:1
Layer resolution (mm)	10–50

2.3. Life Cycle Analysis

The environmental impacts and burdens on the ecosystem of production, construction, operation, and disposal stages over the life cycle of a system was quantified using the LCA systematic framework. The international organization for standardization (ISO) developed ISO 14044 and ISO14045 to unify the approach of evaluating the load on the environment, address the resulting ecological impacts and identify potential performance enhancement over the lifecycle of the systems [22,23]. Two LCA approaches are commonly investigated in the construction industry, namely, cradle to grave and cradle to site. The first method includes all materials and processes in a comprehensive assessment, while the second approach focuses on certain aspects of the construction project such as the materials [17]. In this study, a cradle to site approach was selected and the LCA was performed in four stages including, goal and scope, life cycle inventory (LCI), and life cycle impact assessment (LCIA) analysis, and results interpretation. Stage one of the LCA involves defining goal and scope as well as the system boundaries and functional unit. The LCI phase includes collection of data, while the third sage (LCIA) examines the contribution of these data to selected impact categories. Stage 4 involves assessment of the results and identifying study limitations. SimaPro 9.0 developed by PRé Sustainability was utilized to implement the LCA framework using Ecoinvent 3.0 [24].

2.3.1. Goal and Scope Definition

The goal of this study is to evaluate the environmental performance of a 3D printed house compared to conventional construction techniques. Measuring the functionality of both construction techniques output was achieved by selecting a reference or a functional unit; 1 m^2 of the single-storey house surface area was selected for simplification of inventory data calculations. Figure 2 shows the boundaries of the examined systems including, production and manufacturing of materials, construction, operation, maintenance, and end of life phase. However, the LCA assessment was limited to material extraction, construction, energy consumption, and transportation during the operation phase. Similar components in both structural systems were excluded i.e., earthworks, HVAC systems and finishes. The labour and end of life phase were excluded from the study as they were found negligible [17]. Moreover, all of the reviewed literature (Table 1) excluded the end of life or demolition phase as a result of lack of available data.

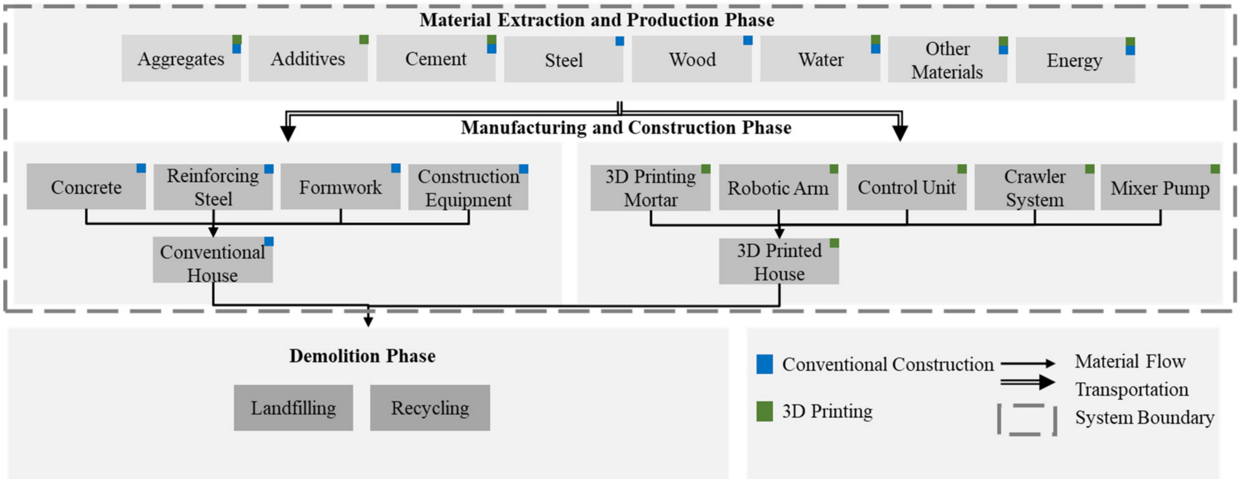

Figure 2. System boundaries of 3D printing and conventional construction of the examined house.

2.3.2. Life Cycle Inventory

The input data related to 3D printing and conventional construction were gathered from local suppliers, Ecoinvent database and the literature. Such technical data include foreground components such as quantity of materials, transportation, and energy consumption. Moreover, background data of the environmental burdens were assigned to the foreground processes and components. Table 5 lists the inventory data of the examined structural systems, in which energy consumption of the equipment utilized on-site can be measured from the power demand and operation time of such machinery.

Table 5. Life cycle inventory data of the examined systems per functional unit.

Data	3D Printing *	Conventional Construction **
Steel (kg) ***	-	200
Fly Ash (kg)	170	-
Micro silica (kg)	180	-
Superplasticizer (kg)	10	-
Viscosity modifying admixture	98,103	-
Cement (kg)	430	300
Coarse Aggregate (kg)	-	4680
Fine Aggregate (kg)	645	4680
Water (kg)	180	190
Concrete (kg)	-	340
Wood (m^2)	-	5
Energy Consumption (kWh)	21	68 ***
Material Transportation Distance (km)	100	100
Printer Transportation Distance	6500	-

* [25] ** [2,26] *** [27].

2.3.3. Energy Consumption

The energy consumption rates in the construction sector reach up to 40% of the total energy demand [28]. The primary electricity consuming sources are the cooling systems as a result of the harsh climate of the UAE with temperatures reaching up to 48 °C, hence the construction sector is constantly exploring efficient heat insulating materials to prevent overheating and humidity increase. The European commission has reported that buildings are responsible for at least 40% of the total energy consumption Particularly, air conditioning is a major energy consuming element in a building, hence reduction of cooling load demand by thermal insulation through construction materials inducing low heat transfer can save up to 50% of the building energy demand [29]. The energy savings for the 3D-printed and conventional concrete house were calculated based on the difference between the microclimate and the air temperature surrounding the structure as well as the thickness of the structural elements (external walls and roof). The ISO standard (EN ISO 6946:2008) reported the key factor to indicate the thermal properties of the building is heat transfer (U) in which lower U-value indicates higher energy savings [30]. The U-value [31] and the energy transfer or heat flow (Q) [32] were calculated using Equations (1) and (2) [33,34]:

$$U = \frac{k \times A}{l} \tag{1}$$

$$Q = \Delta T \times U \times A \tag{2}$$

where U is the thermal transmittance ($W/m^2 \cdot K$), k is the thermal conductivity of a material ($W/m \cdot K$), A is the plane area of (m^2), l is the thickness of material (m), Q is heat flow (W), and ΔT is the temperature difference between external and internal structural element surface (°C). The heat transfer through individual rooms of the house, the windows, and doors was calculated. The design temperature outside and inside the house was specified by local guidelines as 46 °C and 24 °C, respectively. Moreover, the U-value of the floor and roof slabs were obtained from local standards and they were compared to ASHRAE (American society of heating, refrigerating and air-conditioning engineers) specifications based on perimeter to area ratio and thermal resistance values [33,34].

2.3.4. Life Cycle Impact Assessment

The environmental impacts of the digitally fabricated and conventionally built house were estimated using ReCiPe 2016 V1.03 midpoint (H) indicators [35]. The method represents the impacts of a global representative and addresses 18 different categories. The impact mechanisms include climate change or global warming potential (kg CO_2 eq) ozone layer depletion (kg CFC-11), terrestrial acidification potential (kg SO_2), marine eutrophication (kg N), freshwater eutrophication (kg P), human toxicity (kg 1,4dichlorobenzeen), particulate matter formation (kg PM2.5), ionizing radiation (kBq Cobalt-60), photochemical oxidant formation (kg NMVOC), terrestrial, freshwater, and marine ecotoxicity (kg 1,4dichlorobenzeen), agricultural and urban land occupation (m^2), freshwater depletion (m^3 water consumed), mineral resource depletion (kg Copper (Cu)), and fossil fuel scarcity (kg oil) [35]. The impact categories represent the effect on the environment and are based on weighted and normalised factors [36].

2.4. Life Cycle Costing Analysis

The financial viability of 3D printing and conventional construction techniques was investigated by calculating the construction and energy use costs. The capital cost of the examined projects included procurement and manufacturing of construction materials e.g., cement, steel, wood, aggregates, and admixtures, as well as construction activities. The present value (PV) of the electricity costs of the systems was estimated for a period of 50 years, which was carried out via LCCA framework to estimate the present worth of the energy consumed in the 3D printed and conventionally constructed house. Moreover, the time value of the cashflow was considered in this study using a local-based discount rate of 3% [37]. Equation (3) is used to calculate the present value [38]:

$$PV = \sum_{t=1}^{T} C_{o,t}(1 + r)^{-t} \tag{3}$$

where C_o is the cash outflow (USD) of year t, r is the discount rate (%), and T is the lifespan of the project.

2.5. Eco-Efficiency Analysis

Selection of an optimum alternative and identification system trade-offs can be accomplished through an eco-efficiency analysis. Such analytical framework functions by agglomerating LCC and LCCA results, which are plotted into a single portfolio [23]. The ratio method is the most commonly used approach to determine the eco-efficiency of a system or a product [39–41]. In this study, the ratio method was employed which is defined as the ratio of economic indicator to environmental performance of the examined system as shown in Equation (4) [41].

$$\text{Eco} - \text{efficiency} = \frac{\text{Environmental Performance}}{\text{Economic Value}} \tag{4}$$

The Environmental indicator in this research study was retrieved from the LCA SimaPro software represented by a normalized and weighted single value aggregating all the midpoint categories. Moreover, the present value was utilized which corresponds to the economic indicator of each assessed system. An eco-efficiency portfolio combining environmental and economic scores was plotted for the selection of the most eco-efficient system and assessing the trade-off among the studied alternatives.

3. Results and Discussion

3.1. Environmental Analysis

The LCA results analysed in this section represent a comparison of additive manufacturing and conventional construction techniques in terms of the environmental impacts. The environmental impacts of the studied scenarios were calculated via SimaPro in 4 stages—characterization, damage assessment, normalization, and weighing [24]. During the first stage (characterization), the materials were multiplied by a factor that represents the relative contribution. The damage assessment facilitates the use of endpoint categories, where impacts with the same units can be added. Normalization stage enables comparison among scenarios in which the impacts are divided by a reference. The weighing phase is typically performed by multiplying the impact categories with a factor and adding them to result in a single score. This score is an indication of the total impacts. Table 6 provides detailed environmental performance scores for each impact category of the 3D-printed and concrete-based house. Most impact categories had significantly higher values for the conventional construction method. Among the highest scored impacts in the conventionally built house were global warming, non-carcinogenic toxicity, water consumption, carcinogenic toxicity, and fossil resource scarcity. Cement production contribution to global warming potential (1154.2 kg CO_2 eq) was approximated to be 70%. Moreover, reinforcing steel production and manufacturing comprised 98 and 97% of the total emissions of non-carcinogenic and carcinogenic toxicity with relative impact of 675 and 169 kg 1,4-DCB, respectively. Furthermore, fossil scarcity (150 kg oil eq) was attributed to the manufacturing of steel (60%) and cement (38%), and the high-water consumption was mainly due to addition of water during concrete manufacturing. The Global warming potential and water consumption had relatively high impacts for the 3D-printed house. As for the concrete constructed house, global warming potential (609 kg CO_2 eq) was high due to production and manufacturing contributing 97% and water consumption with a volume of 184 m^3 per functional unit was attributed to water demand during 3D mortar preparation. The endpoint indicators were represented by a single score that combines all the inventory results in one factor. For the 3D-printed and the conventional house, the human health category had substantially higher impacts compared to effect on ecosystem and natural resources indicators. Human health category caused 93 and 88% of overall emissions of the conventional construction and 3D printing scenarios, respectively.

The obtained results from SimaPro were normalized and weighted to provide holistic assessment. Normalization enables for a coherent interpretation of the characterized environmental impact categories through referring to a reference scheme, followed by weighting which emphasizes the relative significance of the impact indicators. Figure 3 shows the relative environmental impacts of the examined systems analysed based on different impact categories. It is evident that 3D printing has an overall lower impact across all categories. The 3D printing scenario performed more than 50% better for the majority of the categories which may be attributed to the material efficiency compared to the conventional scenario. Typically, conventional building requires formworks and reinforcing steel, which are absent in the 3D printing scenario. Therefore, all emissions related to the production, manufacturing, transportation, and fabrication of materials are reduced. The damage to the ecosystem was minimal where the midpoint categories pertaining to freshwater marine, and terrestrial species had relatively low percentage (0–7%). Though all categories of 3D printing had lower impacts, the water consumption category was only 20% better for the 3D printed house due to high water use during cement production processes and electricity generation, which is common to both construction methods.

Table 6. Environmental inventory results of the examined structural systems.

	Impact Category	3D Printing	Conventional Construction
Midpoint Indicator	Carcinogenic Toxicity (kg 1,4-DCB)	4.30	168.60
	Fossil Resource Scarcity (kg oil eq)	2.90	150.00
	Fresh Water Ecotoxicity (kg 1,4-DCB)	0.23	23.90
	Fresh Water Eutrophication (kg P eq)	0.002	0.20
	Global Warming (kg CO_2 eq)	608.55	1154.20
	Ionizing Radiation (kBq Co-60 eq)	2.58	16.50
	Land Occupation (m^2a crop eq)	0.40	6.80
	Marine Ecotoxicity (kg 1,4-DCB)	0.34	33.60
	Mineral Resource Scarcity (kg Cu eq)	0.08	30.80
	Non-carcinogenic Toxicity (kg 1,4-DCB)	11.9	675.10
	Ozone Depletion (kg CFC11 eq)	1.90×10^{-4}	3.20×10^{-4}
	Particulate Matter Formation (kg PM2.5 eq)	0.02	1.70
	Photochemical Oxidant Formation (kg NO_x eq)	0.06	2.84
	Terrestrial Acidification (kg SO_2 eq)	2.50	4.10
	Water Consumption (m^3)	183.95	233.35
Endpoint Indicator	Human Health (Pt)	5.30	18.63
	Ecosystems (Pt)	0.64	1.30
	Resources (Pt)	0.05	0.20

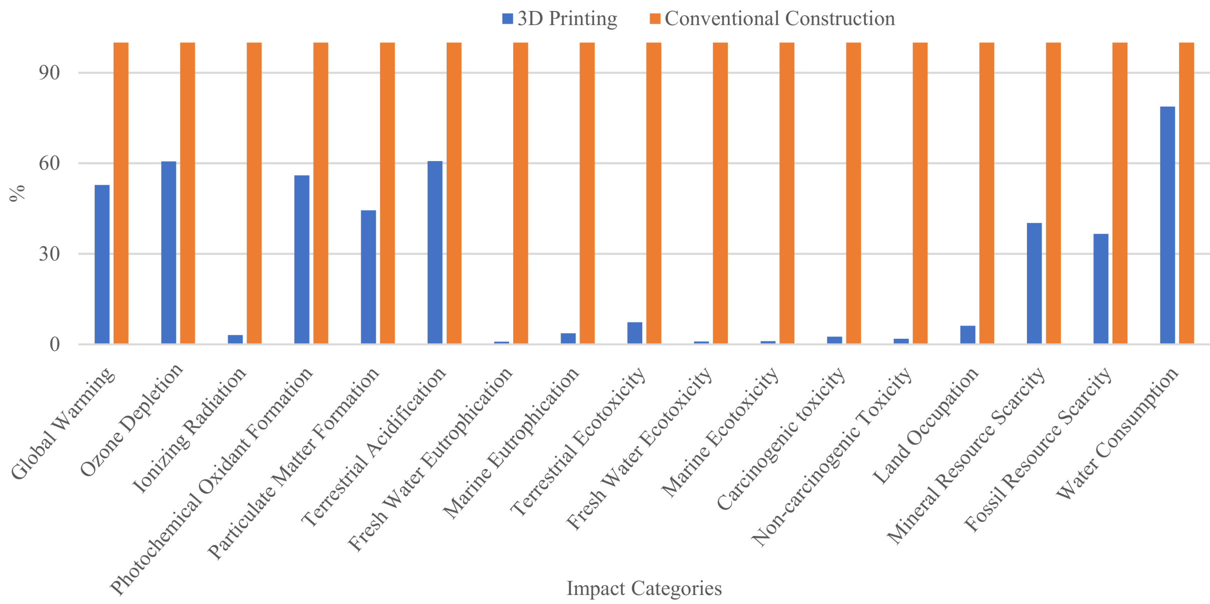

Figure 3. Relative environmental impacts of 3D printed and conventional constructed houses.

In the digitally fabricated house, cement production phase contributed (more than 95%) to most of the impact categories i.e., global warming, ozone depletion, terrestrial acidification and ecotoxicity, human carcinogenic impacts, and fossil and mineral resource scarcity as shown in Figure 4. Moreover, material extraction and production of the utilized admixtures was a major contributing process to land occupation, freshwater eutrophication, ionizing radiation, marine and freshwater ecotoxicity, and non-cariogenic human effects, with 99, 98, 97, 61, and 40%, respectively. Electricity and transportation obtained the lowest ratio in all environmental impact categories with impacts ranging between 0 to 2%.

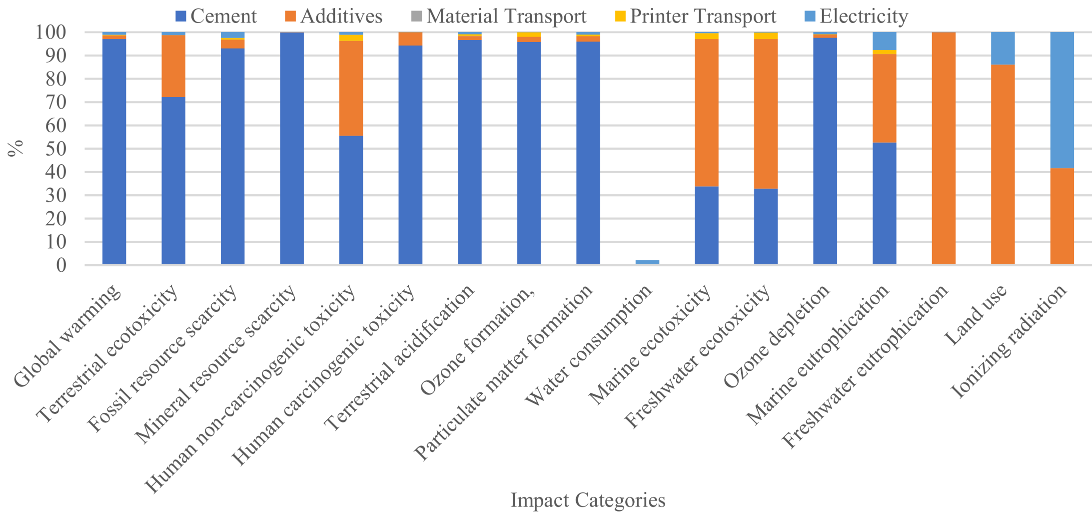

Figure 4. Contribution of 3D printing processes to the overall environmental impact.

The contribution of the different impacts i.e., production of cement and steel, manufacturing of concrete, transportation, as well as electricity production are shown in Figure 5. The cement production shows the highest contribution in all impact categories due to significant consumption of raw materials and energy, the greenhouse gas emissions during manufacturing phase, and the release of bulk amounts of waste. Moreover, the environmental analysis revealed that reinforcing steel production and manufacturing processes had a primary impact on freshwater eutrophication (99%), land occupation (98%), terrestrial and marine ecotoxicity (93%), carcinogenic, non-carcinogenic and freshwater ecotoxicity (89%), fossil resource scarcity (60%), and global warming (41%). Similar to the conventional house results, the electricity scored the lowest in all categories except ionizing radiation (11%). Overall, the exploitation of materials, energy use, and transportation during manufacturing of concrete components poses the highest environmental risks as can be deduced from Figure 5.

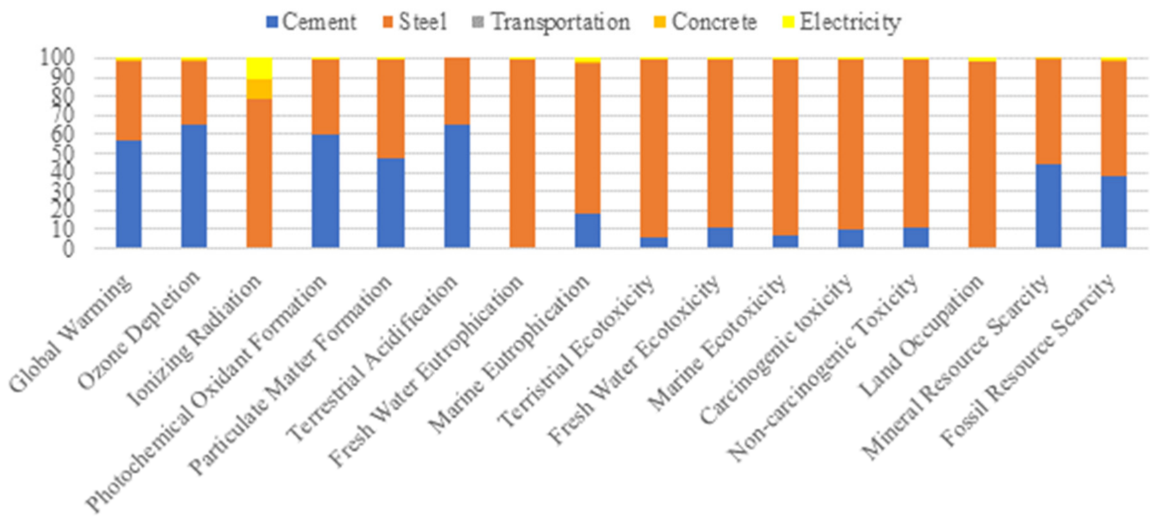

Figure 5. Relative contribution of conventionally constructed house processes to the environmental impact.

The results of this study agree with the outcomes of [2,12,17], which reveals that 3D printing structures outperform the conventional construction methods in terms of overall environmental impacts. The main difference in this study was conducting the analysis for the entire house, whereas [2,12] studied the impacts on individual elements (wall, roof, and a concrete slab) with varying design complexities and included the operation phase for the self-shading wall element. Moreover, the 3D printing mortar ratios and components in this study was tested for an implemented project in the UAE, while Agustí-Juan and Habert [2] adopted a fiber reinforced concrete from the literature and Alhumayani et al. 16 tested out three different mixes also compiled from the literature and compared the results. Furthermore, Agustí-Juan et al. [12] designed a high performance 3D printing concrete which was found to increase the GHG emissions when compared to conventional concrete mix.

3.2. Operational Energy

The cooling energy demand for the 3D-printed and conventionally constructed house was calculated considering the thermal transmittance of the construction mortars. Table 7 summarizes the cooling systems calculation results for the 3D-printed and conventionally constructed house. Overall, the total heat transfer (gain) of the conventional building system was 5% more than the 3D printed house. The 3D printed house acquired less heat gain due to higher material thickness and thermal transmittance (K). In other words, the lower thermal conductivity and thickness of materials the lower heat transmission. Another contributor to low heat conduction is U-value, where the slabs of a 3D-printed house had lower U-values compared to the conventional concrete house. On the other hand, the insulating properties of the 3D-printed wall including an air cavity had a much higher U-value (3.75 W/m^2·K) which is in close proximity to the concrete wall (3.6 W/m^2·K).

Table 7. Insulation parameters and cooling demand results.

Parameter	3D Printing						Conventional System					
	Wall				Floor	Roof	Wall				Floor	Roof
K (W/m·K)	0.92						0.55					
R (m^2·K/W)	0.08				0.33	0.16	0.09				0.46	0.45
Thickness (m)	0.08				0.3	0.15	0.05				0.25	0.25
U (W/m^2·K)	3.75 *				0.27	0.10	3.6 *				0.44	0.44
Q (W)	W1 2189	W2 3424	W3 3123	W4 2783	201	519	W1 2157	W2 3374	W3 3077	W4 3742	858	858
Σ Q ** (BTU/h)	49,269						52,098					

* The wall U-value includes air cavity with thickness 0.04 m and R of 0.12. ** The total heat gain includes heat from doors and windows.

3.3. Economic Assessment

The economic analysis findings of the selected structural systems are summarized in Table 8. The results comprise capital costs of materials (local-based) including civil works and operational expenditures of cooling systems. The conducted present value over a 50-year design period indicates that conventional construction technique was the most expensive alternative (USD81,064) which was double the cost of the 3D printing. This can be attributed to the cost of concrete, and formworks which comprise 51 and 24%, respectively. The capital expenditures of concrete are associated with the purchase and manufacturing of various sub-components, mainly aggregates (USD10,795). Although the steel cost rate (USD500/ton) was the highest, it had the least contribution to the overall cost. On the other hand, the 3D printing technology was found to be 49% cheaper than the conventional construction scenario. The 3D printing excludes multiple aspects including construction components, e.g., concrete and formworks, as well as labor cost, thus reducing the overall capital costs. These results are in line with [18], where the 3D printing of houses contributed to 35% savings compared to conventional construction.

Table 8. Capital costs of construction components and operational expenses.

Component	Rate (USD/ton)	3D Printing	Conventional
Cement	15	45	44
Additive	220	8	-
Aggregate	15	10,795	10,795
Steel	500	-	1308
Concrete	$60/m^3$	-	25,147
Formwork	$27/m^2$	-	11,933
Present Value (USD)	**-**	**−40,955**	**−81,064**

Note: Positive present values signify revenues, whereas negative values represent costs.

4. Eco-Efficiency Analysis

The depicted results of economic and environmental performance ratios were plotted in an eco-efficiency portfolio as illustrated in Figure 6. The top-right corner distinguishes the low eco-efficiency alternative, while the bottom left corner of the plot area identifies the high eco-efficiency option. The conventional construction house had significantly lower eco-efficiency compared to 3D-printing. Upon comparing the operation phases of both houses, the results reveal similar eco-efficiency scores, which coincides with the LCC and LCA analyses. Moreover, the eco-efficiency index diagram orders the alternatives from the highest (bottom) to lowest (top) eco-efficiency. The 3D printing method was found to be the highest and conventional construction acquired the lowest eco-efficiency. The findings of eco-efficiency analysis showed that operation phase alone was negligible in the selection process of the optimum alternative, nevertheless the combined construction and operation phase revealed 3D-printing as the most eco-efficient option.

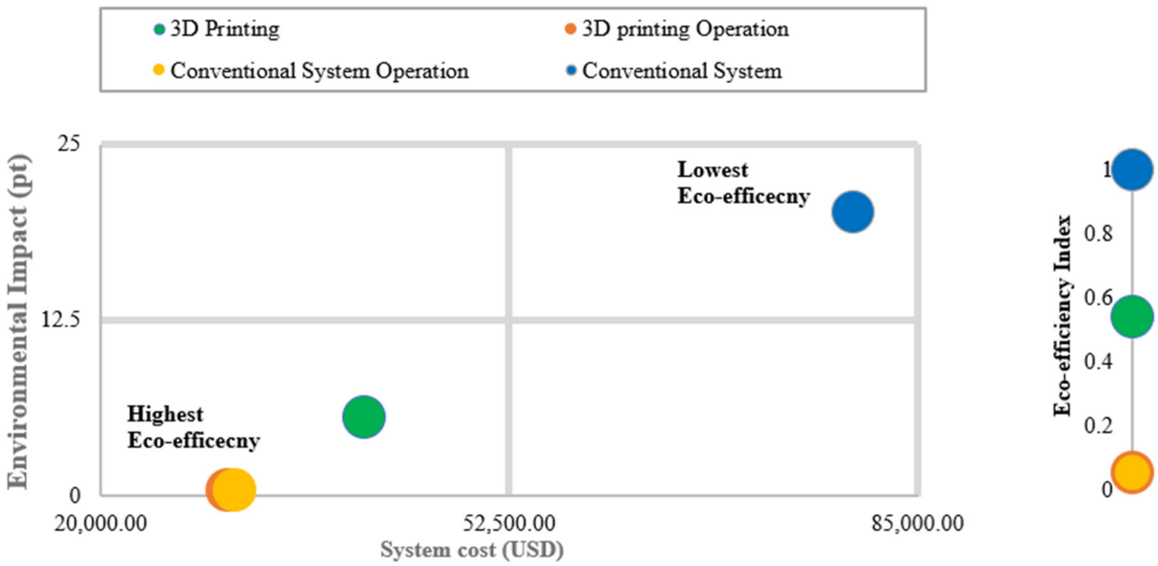

Figure 6. Eco-efficiency portfolio of 3D-printed and concrete-based house construction and operation phases.

5. Sensitivity Analysis

Several factors such as system boundaries, assumptions, and accuracy of inventory data affect the certainty of LCA and LCC results. Moreover, the 3D printing technology is still in the exploration and development stage and the data were compiled from the literature. A sensitivity analysis was conducted to account for the uncertainties in this study where the selected parameters are listed in Table 9. Different 3D printing binder mixtures were evaluated in the analysis to investigate the environmental impact of cement and coarse aggregates as they acquired the highest scores in the LCA results. The conventional concrete mix was also evaluated to investigate the effect of varying concrete and steel quantities [2,42].

Table 9. Parameters utilized in the sensitivity analysis for 3DCP and Conventional scenarios.

Parameter		**Reference Value**		**Sensitivity Analysis Options**			
		3D Printing	**Conventional**	**3D Printing ***		**Conventional**	
				Mix 1	**Mix 2**	**Mix 1 ****	**Mix 2 *****
Life Cycle Analysis	Steel (kg) ***	-	200	-	-	560	61
	Fly Ash (kg)	170	-	165	165	-	-
	Micro silica (kg)	180	-	83	83	-	-
	Superplasticizer (kg)	10	-	8.3	8.3	-	-
	Viscosity modifying admixture	98,103	-	98,103	98,103	-	-
	Cement (kg)	430	300	580	300	53	10
	Coarse Aggregate (kg)	-	4680	1241	64	1135	1280
	Fine Aggregate (kg)	645	4680	-	-	-	2
	Water (kg)	180	190	232	190	231	822
	Concrete (kg)	-	340	-	-	7	140
	Brick (kg)					197	-
	Wood (m^2)	-	5	-	-	77	25
	Energy Consumption (kWh) ****	21	68	2.26	2.26	11	18
Life Cycle Costing	3D Printer (USD)	183,000	-	-	-	-	
	Electricity Tariff (USD/kWh)	0.081		0.07–0.101			

* Adapted from [15] ** [2], and *** [42], **** The energy consumed by machinery.

The concrete, steel, and cement production accounted for the highest environmental scores in the performed LCA. Figure 7 illustrates the results of the sensitivity analyses for the different 3DCP and Conventional mixtures. The results are presented relative to the conventional base scenario which obtained the highest impacts in all categories. The analysed mixtures had relatively small impacts contributing to 0–3% in all categories. Nevertheless, the 3DCP mix 1 and 2 contributed to the highest water consumption (474 and 391 m^3, respectively), followed by conventional mix 1 (390 m^3), conventional base scenario (233 m^3), the 3DCP base scenario (184 m^3), and the least water consumption was attained by conventional mix 2 (110 m^3). These results led to the conclusion that reducing cement quantities in 3DCP binder can reduce the overall environmental impacts by 90%. In conventional construction techniques replacing some concrete elements with bricks (such as conventional mix 2) can also reduce the environmental deterioration.

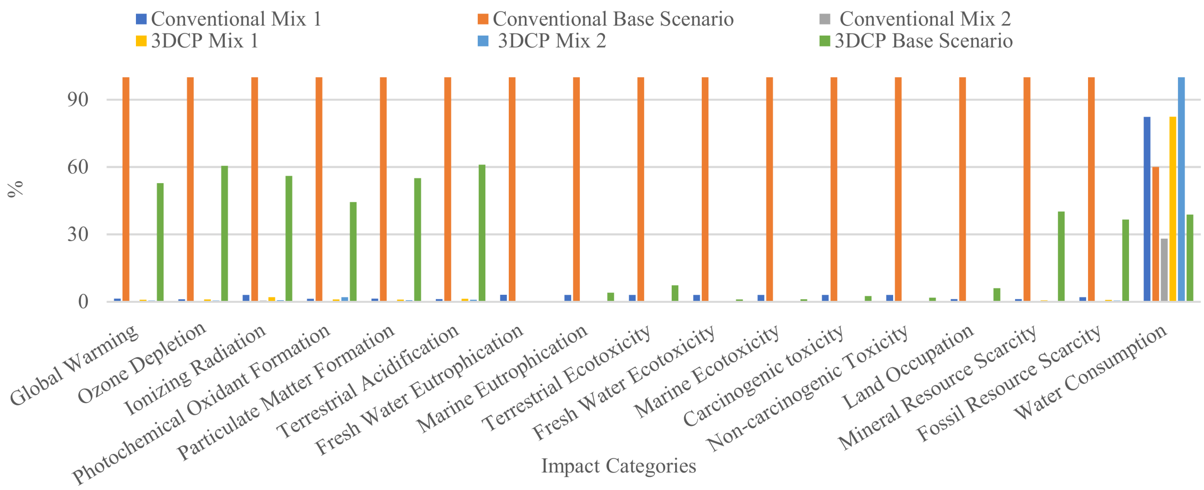

Figure 7. Sensitivity analysis results of different conventional and 3D concrete printing (3DCP) mixtures.

The LCC results of the different mixtures reveal significant differences from the original scenarios (Table 10). The 3DCP mix 1 and 2 showed almost similar results with a decrease of 20% from the original mix. This decrease can be attributed to the reduction of cement in mix 1 and mix 2. Conventional concrete mixtures 1 and 2 obtained a total cost of USD 33,073 and 31,451, respectively which is almost 60% less than the base scenario. Moreover, the cost of the 3D printer was added to the 3D printed house scenario while keeping all the other parameters constant. The present value was found to be USD 225,391 (82% increase in expenditures). Since the technology is still in the exploration stage, a renting cost is yet to be accounted for in future 3D construction projects. Different electricity tariffs ranging between 0.07 to 0.1 were investigated. For low electricity tariffs, the costs of the 3D printing scenario decreased by 5% and increased up to 25% for higher ranges. Similarly, the costs of the conventional scenario decreased by 7% and increased up to 7% for higher ranges.

Table 10. Life Cycle Costing of the different sensitivity analysis alternatives.

Sensitivity Analysis Options		Present Value (USD)
3DCP Mix 1		−32,664
3DCP Mix 2		−32,588
Conventional Mix 1		−33,073
Conventional Mix 2		−31,451
3D Printer		−225,391
Electricity Tariff	3DCP	−38,972 to −51,427
	Conventional	−75,741 to −87,483

Data uncertainty and limited availability typically affects the life cycle assessment results. Figure 8 shows a +10% variation of the LCC and LCA parameters studied in the current research. The figure revealed a correlation of operation of both 3D printed and conventional scenarios. Nevertheless, the construction of conventional system had the greatest environmental impact and greatest cost with the variation.

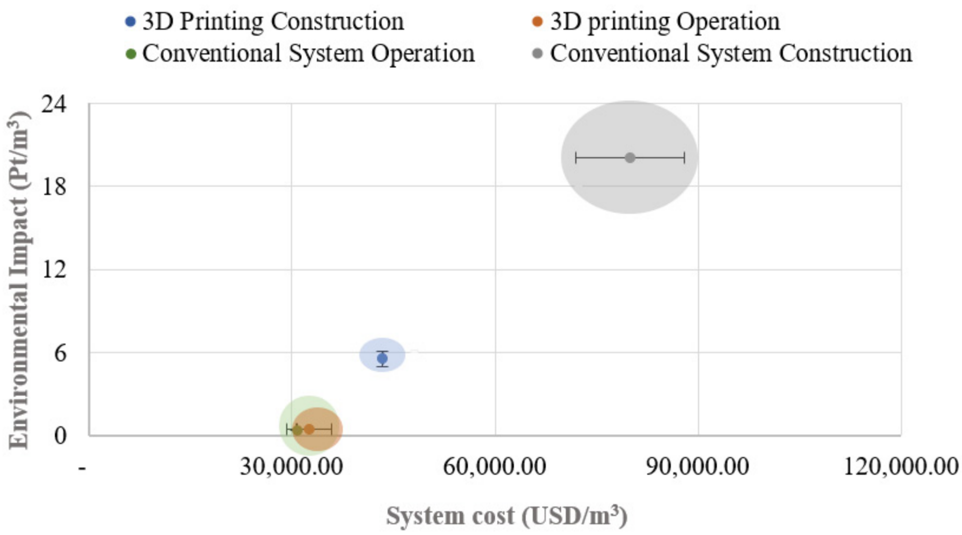

Figure 8. Uncertainty analysis of with +10% variation of 3D printing and conventional construction scenarios.

6. Study Limitations

Based on the conducted structural, environmental, and economic assessments, 3D printing is a viable alternative to conventional construction techniques. However, the findings of this comparative study were limited due to the unavailability of some important data, such as, (1) characteristics of the mortar used in 3D printing process, (2) varying ratios of conventional concrete ingredients, (3) limited number of investigated structural elements, (4) exclusion of sub-structure system and end of life phase, and (5) the common processes and components among the examined alternatives were not included, thus only relative environmental impacts were quantified, (6) inadequacy in 3D printing speicifc processing and (7) data inventory was calculated from diverse sources as a result of lack of data.

7. Conclusions

The evaluation of digital fabrication technologies, particularly 3D printing, has been adopted to enhance environmental performance and economics. This study compared (1) additive manufacturing by means of extrusion method and (2) conventional construction using cast in-situ concrete. The comparative analysis was performed on a single-storey house in the UAE from environmental and economic perspectives. The analysis utilized LCA using midpoint impact methodology ReCiPe 2016 to measure the relative environmental burdens. The LCCA analytical framework was conducted to determine the financial feasibility of the examined scenarios. The results of the LCA and LCCA analyses were combined using a ratio method to determine the system with the higher eco-efficiency. LCA analysis revealed better environmental performance of the 3D printing method due to the absence of several components, such as formworks, steel reinforcement and the lower use of materials, compared to conventional construction alternatives. From an economic perspective, the LCCA indicated that 3D printing is 78% more profitable than its conventional counterpart. The eco-efficiency analysis revealed that 3D printing was the optimum choice. The sensitivity analysis revealed that decreasing cement ratios in 3D printing mortars can significantly decrease the environmental impacts. In this study the 3D printing construction technology showed a better overall eco-efficiency. However, it is acknowledged that the number found in this study may differ for different comparative analysis conditions.

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Abbreviations

3DCP	3-D Concrete Printing
ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building information modelling
CAD	Computer aided design
GWP	Global warming potential
EI	Eco-efficiency index
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
ISO	International organization for standardization
LCA	Life cycle assessment
LCC	Life cycle costing analysis
LCI	Life cycle inventory
LCIA	Life cycle impact analysis
PV	Present value
STL	STsereo Lithography
UAE	United Arab Emirates

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