A Generic 3D Printing Life Cycle Assessment (LCA) Framework for AEC Applications

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Abstract –

Amidst the increasing adoption of three-dimensional printing (3DP) in the architecture, engineering, and construction (AEC) industry, there exists a notable research gap concerning the quantification of its environmental impact. More importantly, there is a lack of a generic framework that can be employed for different material types and methods. Therefore, this research aims to develop a generic 3DP life cycle assessment (LCA) framework pertaining to the AEC industry. To substantiate the viability of the proposed framework, a meticulous case study was conducted. Focused on the LCA of a concrete 3DP process employed in constructing a two-story residential villa in the United Arab Emirates (UAE), the case study employed the contour crafting 3DP technique. A detailed cradle-to-construction LCA was executed using a functional unit of 1m^3. Data compilation involved synthesizing information from literature sources and utilizing DesignBuilder™ software. The embodied carbon analysis of the case study yielded insightful results, indicating that the contour crafting technique emitted approximately 103,135 kg of carbon. Significantly, concrete emerged as the predominant construction material, contributing approximately 52% to the total equivalent over the various life cycle stages. Future work warrants further investigation into the mitigation measures to enhance the environmental performance of 3DP within the AEC industry. Additionally, the research encourages the exploration of alternative 3DP construction techniques and diverse project types, thereby broadening the applicability of the developed framework. This research provides a foundation for more sustainable practices and fosters further exploration of the 3DP implementation within the AEC industry.

Keywords –

3D printing; LCA; Construction industry; Embodied carbon

1 Introduction

The inherent nature of the architecture engineering and construction (AEC) industry makes it one of the significant contributors to resource utilization. Therefore, understandably, the environmental impact is considerably high when compared to other industries. According to the statistics, it accounts for about 40% of global energy consumption, 28% of global greenhouse gas (GHG) emissions, and a significant amount of waste is generated [1]. The core of the AEC industry is the use of cement-based and concrete materials. With the growing need for new structures, the utilization of these materials is increasing. The production and utilization of concrete materials in the AEC have been shown to result in detrimental environmental impacts. According to Andrew [2], during concrete production, a large amount of carbon dioxide (CO_2) is released and represents 4% to 5% of worldwide emissions of CO_2.

In recent years, there has been a rise in interest in three-dimensional printing (3DP) technology for automating concrete construction. 3DP is the process of slicing a three-dimensional (3D) computer-aided design (CAD) model into two-dimensional (2D) layers and sequentially printing the materials to construct the full product, layer upon layer. The 3DP process has been widely used in various disciplines and enterprises. However, studies have revealed that 3DP is not commonly employed in buildings, and its applications remain limited [3]. 3DP allows for faster structure development while also reducing building time, labor costs, and waste generation [4]. According to Tinoco et al., [3], it can reduce construction time by 50 to 70 %, labor costs by 50 to 80 %, and waste production by up to 60%. All of these capabilities have raised interest in 3DP in the AEC industry. Despite the research and implementation of 3DP in the field and the documentation of its technological and economic advantages, there has been limited quantitative research on 3DP's environmental performance. Several existing review studies, such as [5], have attempted to examine the applicability of life cycle assessment (LCA) for 3DP.

To further emphasize the need and highlight the gap in the existing literature, this research first systematically and critically analyzed the extant literature on 3DP's LCA, the summary of which was presented earlier. Quantifying this further, several recently published articles based on data from scientific databases such as Web of Science and Scopus were retrieved since 2011. It was observed that approximately 40 research articles were published on the topic of LCA in 3DP. The search strategy employed a comprehensive set of keywords to obtain relevant research articles. For example, the keyword search string criteria used are as follows: Keywords ("LCA" OR "life cycle" OR "life cycle analysis" OR "Environment*" AND "assess*") AND ((3d OR 3-d OR 3d-) AND print*) OR ("Additive manufacturing") AND ("Construct*" OR "Build*") AND ("Concrete" OR "cement-based" OR "cementitious" OR "geopolymer" OR "cement")]. The 'OR' and 'AND' are boolean operators used to combine or exclude specific terms to refine search results. Specifically, the usage of 'OR' between two terms will return results that include either one of the terms or both. For example, "LCA" OR "life cycle" will return results containing either "LCA", "life cycle" or both. On the other hand, the usage of "AND" between two terms will return results that include both terms. For example, "3d AND print" will return results that contain both "3d" and "print." To summarize, the usage of "OR" broadens the search whereas the usage "AND" narrows down the search. The overarching idea of the designed search string is to retrieve literature specifically focused on the LCA of the concrete 3DP process. It encompasses various terms related to life cycle analysis, environmental assessment, 3DP technologies (including alternative spellings), additive manufacturing, and specific materials like concrete, cement-based materials, and geopolymers. This comprehensive search strategy aims to identify the most relevant publications related to the environmental impact of 3DP in the context of concrete construction processes. However, the number of papers containing LCA results is less than 30, most of which were focused on specific material types. Therefore, this research concentrated on LCA for 3DP regardless of material type.

Additionally, [3] a recently published review research focused on the LCA of cementitious materials for concrete 3DP. They found that there are still very few published papers with LCA results of concrete 3DP. The total number of papers from 2016 to 2021 is only 15 papers, which are [1,6–19]. After reviewing these articles, it was observed that the majority of 3DP LCA investigations were conducted recently, beginning in 2016. Europe, where 3DP research is in its mature phases, has made the largest contributions to the field. China is the second most important contributor to this sector. Other countries appear to be less prominent, and only two studies were conducted in the Middle East region.

For the LCA details, most articles employed cradle-to-gate system boundaries. There was, however, much diversity in the selection of the functional unit, making it difficult to compare based on this factor. Despite the minimal number of research articles, there was a wide variety of applications. However, the majority of the research used 3DP to print walls. The most researched material was concrete with cement, aggregate, additives, and water. The most popular database utilized in the studies for the life cycle inventory (LCI) is Eco Invent (https://ecoinvent.org/), which has different versions. Gabi database (https://sphera.com/product-sustainability-gabi-data-search/) is the second most used one. In addition, some investigations utilized data from the literature as well. It is thus evident that the existing literature lacks a generic framework to conduct LCA for 3DP in the AEC industry that is not specific to a material type, functional unit, and application.

To address the gap in the literature, this research proposes a generic framework methodology to perform a Life Cycle Assessment (LCA) of the concrete 3DP process in the AEC industry to evaluate its environmental impacts. The evaluation will analyze one specific technique of 3DP used widely in the AEC industry. Therefore, the objectives of this research are to a) Develop a generic framework to conduct LCA of concrete 3DP pertaining to the AEC industry; b) Implement and validate the developed framework through a case study to investigate the CO_2 emissions and identify the materials that contribute most significantly to CO_2 emissions.

2 Proposed 3DP LCA Framework

Figure 1 shows the overview of the proposed research framework to achieve the above-mentioned objectives. Broadly categorized, the framework follows a three-stage procedure. The first stage is to define the purpose of the assessment, the system boundaries, and the functional unit for comparison. The second stage is to collect and quantify data regarding the inputs and outputs of the system. This includes raw material extraction, energy use, water use, emissions, and waste generation. The third and the final stage is to assess the potential environmental impacts. Each of the following tasks involved in these stages is discussed in detail in the sub sections below.

2.1 Define Goal and Scope

The goal and scope definition stage is the foundational stage of an LCA, where the parameters of the system are established. Literature reviews and in-depth analyses of previous studies can be used as tools to identify the construction scenarios. In this stage, the goals of the assessment are clearly stated, which includes defining the reasons for conducting the research and the intended application of the results as suggested in [8]. In addition, define the system boundaries, which may range from the materials production to the end-of-life disposal. This delineation is crucial as it sets the limits for the study and ensures the consistency of the data collected. The functional unit, which is the measure to which all inputs and outputs are related, is also defined during this stage, providing a reference to which the performance of the product system is compared.

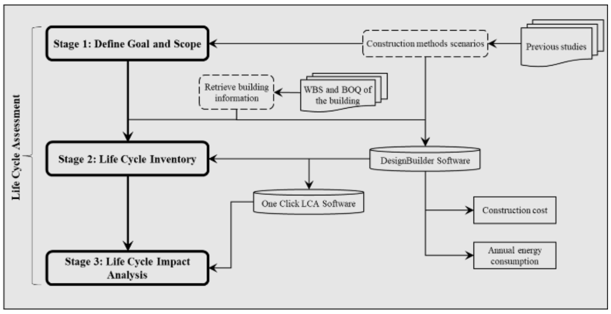

Figure 1. Overview of the proposed 3DP LCA framework.

2.2 Life Cycle Inventory

Life cycle inventory (LCI) is a critical stage of the LCA process. The objective of this stage is to collect and gather all relevant data including inputs and outputs of a system. In the context of this study, inputs may include building materials used and the energy consumed during the construction and operation of the construction project. Similarly, outputs can be referred to as the emissions from on-site construction processes and energy use during the operation and maintenance phase of a project. The aim is to create an inventory of every element and energy flow that goes into and out of the product's life cycle, from the extraction of raw materials through the production and use phases to end-of-life. Typically, this can be retrieved from the project documentation such as work breakdown structure (WBS) and bill of quantities (BOQ).

2.3 Life Cycle Impact Analysis (LCIA)

Life cycle impact analysis (LCIA) is the third and final stage in the LCA process, where the environmental impacts associated with the inputs and outputs identified during stage 2, namely LCI, are evaluated. The primary purpose of LCIA is to assess the magnitude and significance of potential environmental impacts using the data gathered in the LCI stage. This analysis involves several steps, including the selection of impact categories, classification, and characterization.

The impacts associated with a product or process throughout its entire life cycle on the environment are categorized into different impact categories, each representing a specific aspect of environmental concern. The choice of impact categories depends on the goals and scope of the LCA study. Common LCA impact categories include global warming potential, ozone depletion, and eutrophication. Classification refers to the assignment of inventory data to the identified impact categories. Characterization refers to quantification of impact magnitude often resulting in a single score per impact category.

For example, in a building project, LCIA could assess the impacts of material extraction, energy use, waste generation, and emissions throughout the building's life span, from the construction phase to the demolition or end-of-life (EOL) phase. Moreover, it could investigate different construction methods and techniques. LCIA stage translates inventory data into a form that can be more easily understood and acted upon. This helps decision-makers identify the most significant environmental issues and the life cycle stages where improvements can be made for more sustainable product systems.

3 3DP LCA Framework Validation

The objective of this section is to evaluate the proposed general 3DP LCA framework through its implementation in a case study and provide a comprehensive evaluation of the environmental impacts of 3D contour crafting in residential construction. To achieve this, each of the sub-sections below follows a systematic approach, beginning with the selection of the 3D construction technique and moving through to the LCIA. This implementation ensures a thorough understanding of both environmental impacts and potential performance enhancements associated with the construction of a two-story residential villa using the contour crafting technique. This approach aligns with the standards set by ISO14044 and ISO14045, focusing on cradle-to-construction analysis. More specifically, sections 3.1 and 3.2 delve into the construction method selection and elaboration on the selected case study. Sections 3.3 to 3.5 follow the implementation and hence the validation of the three-stage generic 3DP LCA framework developed and discussed in section 2.

3.1 Construction method selection

Based on the existing literature, contour crafting printing is one of the most widely adopted and demonstrated construction techniques [20]. Hence, the contour crafting technique is employed for this illustration. However, any 3DP technique can be selected to implement the specified steps within this framework, as the framework is designed to adapt AEC to various printing techniques.

After choosing the technique, the following needs to be done a) define the goal and scope, b) obtain the life cycle inventory, and d) perform impact assessment. The different materials and processes were quantified using the LCA systematic framework. To standardize the method of evaluating the burden on the environment, ISO14044 and ISO14045 were created by the International Organization for Standardization (ISO), addressing the associated environmental impacts and identifying possible performance enhancements during the lifespan of a system [21,22].

Two strategies are commonly used to evaluate the AEC industry: cradle-to-grave and cradle-to-construction. The first strategy evaluates all processes and materials comprehensively, whereas the second strategy concentrates on specific components of project elements, such as materials [16]. This research used the cradle-to-construction strategy, where DesignBuilder™ software [23–25] and OneClick® software [26–28] were used to perform the LCA analysis.

3.2 Description of Case Study

A two-story simulated residential villa was selected for the case study, as shown in Figure 2. Table 1 shows the different characteristics of the chosen villa. It was assumed that the villa was located in Sharjah, United Arab Emirates (UAE) following the typical dimensions and characteristics of the construction in the region. Based on the objective of this research, the selected structure was proposed to be built using the 3D contour crafting construction technique. The villa is mainly a concrete structure, with a plot area of 272 m^2 and a total built-up area of 394 m^2. For the 3D contour crafting, the dimensions of the elements were simply the length of the wall × the width of the wall, which was 30 cm for external walls and 20 cm for internal walls. The timeframe includes all building elements, such as heating, ventilation, and air conditioning (HVAC) systems, lighting, and finishes, to study their impacts.

Table 1 Characteristics of the case study villa

Division	Description
Building	Villa (G+1)
Site	Sharjah, UAE
Lifespan (years)	40
Plot area (m^2)	272
Total height (m)	8
Ground floor (m^2)	197
First floor (m^2)	197
Total (m^2)	394

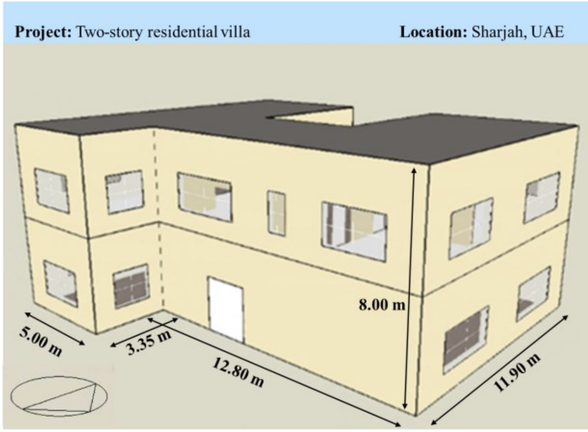

Figure 2. A 3D model of the selected case study villa developed in DesignBuilder™.

3.3 Goal and Scope

The first phase of any LCA is to specify the goal and scope of the proposed system. As discussed, the case study implementation evaluates the environmental impact of the concrete 3DP technique on a residential 2-storey villa. The functional unit was chosen to be 1 m^3 to study the environmental impact of the proposed system. It was normalized to allow for a fair and meaningful comparison between the different materials. A cradle-to-construction LCA was performed in this research, including material extraction, material production and manufacturing, and building construction. Figure 3 shows the general boundaries of the evaluated system in this research. Whereas Figure 4 illustrates the system boundaries for contour crafting, where the system includes different processes and materials such as material extraction, material production and manufacturing, and construction.

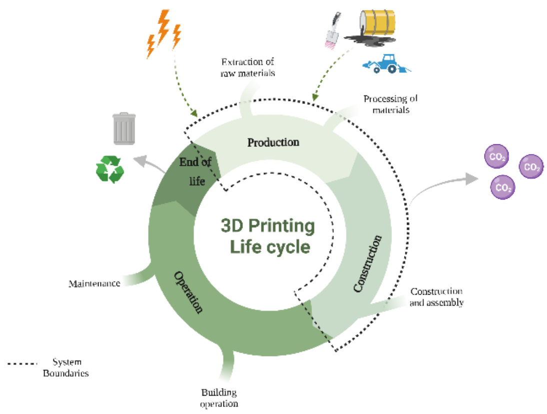

Figure 3. The general system boundary

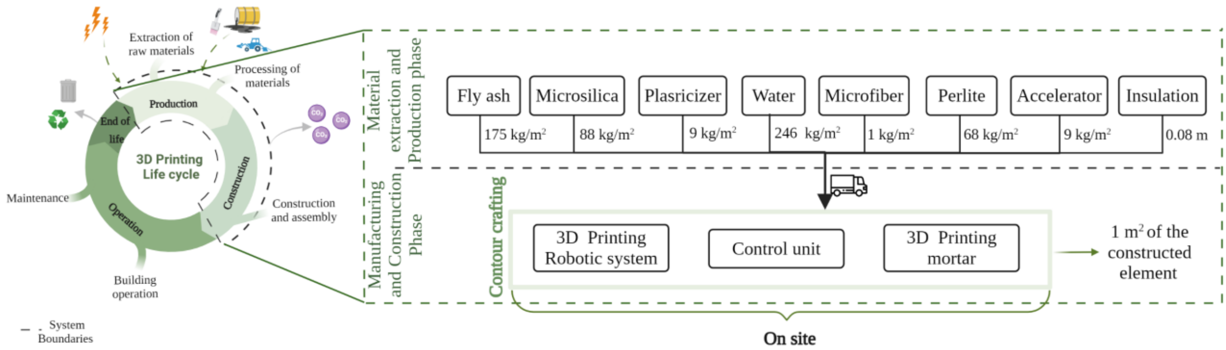

Figure 4. System boundaries of contour crafting for the case study villa

3.4 Life Cycle Inventory

The input data for the contour crafting technique mentioned in the following sections was gathered from the literature [16,29]. The data will include the material mix, amount of each material, transportation, energy consumption, and equipment utilized. Only the production and construction phase elements are presented on the technique flowchart (cradle-to-construction). In the context of the 3D printing construction methods, the concrete mix composition differs from traditional concrete mixes used in conventional construction methods [30,31]. In this scenario, the structure will be built using 3DP technology called contour crafting. In this technology, the structural elements will be built on-site. The functional unit combines all the building elements. The final materials and concrete mix were extracted after reviewing existing literature within the region and by examining a similar project facing comparable environmental conditions [11,29]. Through an in-depth review of their material choices, quantities, and a focus on their consistent water-cement ratio of 0.4 across both studies, the concrete mix used in this scenario is high-performance concrete consisting of fly ash, micro-silica, plasticizer, perlite, microfiber, accelerator, and water. Detailed information on the amount of material obtained from DesignBuilder™ for one functional unit is presented in Table 2. The concrete mix includes innovative materials that serve particular purposes in enhancing performance characteristics. For instance, perlite, which is a lightweight aggregate, was used to replace the sand in the mix. In addition, no steel will be added in the scenario because the mixed used was selected to be a self-reinforced mortar [24], includes components like microfiber and microsilica, which can significantly enhance the tensile strength and durability of the concrete. Moreover, the concrete mix was designed to be a lightweight mix by adding perlite.

Table 2 Data Inventory of contour crafting for the studied villa per functional unit

Material	Quantity
Fly ash (kg)	175
Microsilica (kg)	88
Plasticizer (kg)	9
Perlite (kg)	68
Microfiber (kg)	1
Accelerator (kg)	9
Cement (kg)	614
Water (kg)	246
Insulation (m)	0.08

3.4.1 3DP system

A large-scale 3D printed construction requires an extrusion process, in which the structure is constructed by adding layers of the prepared mortar through a nozzle. For 3DP, the Putzmeister MP25 machine was considered to mix and pump the concrete. The ABB robot (IRB6700) was used to control and automate the nozzle movement. Table 3 summarizes the electric consumption required to print the desired structure based on the machine's characteristics [32,33].

Table 3 Energy consumption of the 3DP system

Equipment	Power required (kW)	Electricity consumption (kWh)
Mixture and pump	7.38	1.55
Robotic arm	3.4	0.71
Total		2.26

3.5 Life Cycle Impact Analysis (LCIA)

The environmental impacts of the proposed villa were evaluated using the integration between DesignBuilder™ and OneClick® (Figure 5). DesignBuilder™ was used to create the 3D model of the proposed villa, including all elements such as construction materials, structural systems, and energy systems. In addition, check the performance of the model, including energy, carbon, lighting, and comfort performance. The model extracted from DesignBuilder™ was exported to OneClick LCA®, which is a comprehensive tool that easily integrates the DesignBuilder™ outputs to assess the environmental impacts. In this study and based on the location, the LCIA was based on the European Standard EN 15978 for conducting whole building LCA [34].

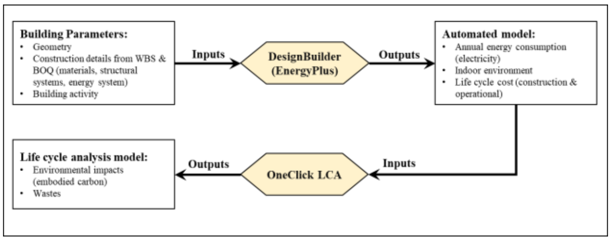

Figure 5. Input-Output diagram of software combinations

4 Results and Discussion

This section represents the LCA results of embodied carbon for global warming over the life cycle stages. LCA of CO_2 is performed in this research to assess the performance of the chosen villa. The goal of the LCA is to evaluate the embodied carbon in kilograms (kgs). The life cycle of CO_2 emission phases can be described as "cradle-to-construction", measuring the emission during material extraction, material production and manufacturing, and building construction.

The LCA results can be divided into different divisions: life cycle stages, contributing materials, annual impacts, elements classifications, and resource types. In this research, the concrete mix of contributing materials is analyzed. The estimated embodied carbon data shown below is based on bulk carbon data obtained from the Bath ICE and other data sources. These results do not cover the embodied carbon associated with building services such as lighting and HVAC equipment. Figure 6 shows the embodied carbon breakdown of contour crafting. The results show that the concrete mix contributed the most, with around 51.73%. Figure 7 shows the LCA for global warming in kg concrete over the life-cycle phases of the villa. Moreover, the total embodied carbon is about 103,135 kg.

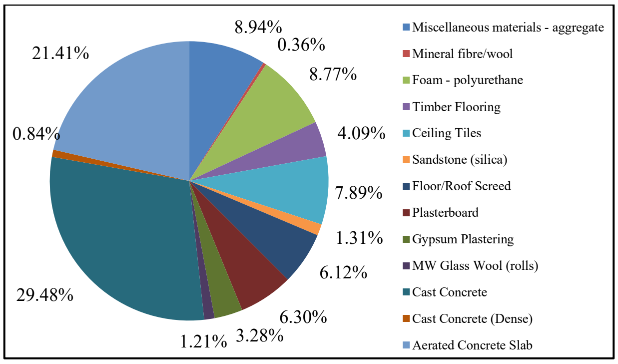

Figure 6. Embodied carbon percentage breakdown for materials

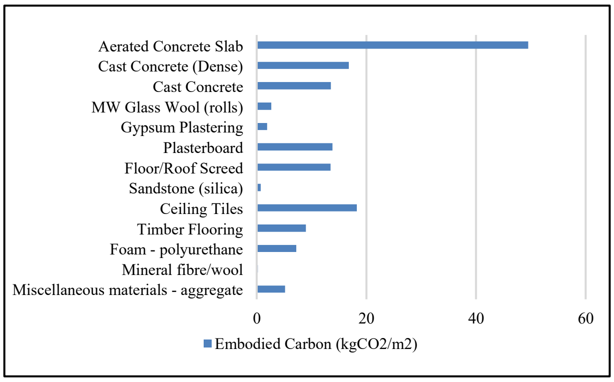

Figure 7. Embodied carbon breakdown in kilogram CO_2 per unit area

The proposed model is designed to evaluate various villas' life cycle CO_2 emissions. Moreover, selecting the most sustainable material and evaluating the buildings' commitment to the CO_2 emission standards laid down in the UAE Green Building Certification Systems is helpful. Most of the data related to the life cycle phases of the DesignBuilder™ are provided by AEC industry professionals working on projects in the UAE or relevant literature. Moreover, the DesignBuilder™ model can be used to obtain additional data related to construction cost and energy consumption.

In order to validate the findings of our study, the total embodied carbon per unit function was compared to the existing literature within the same region constructing the same building type (Residential villa) and adopted the cradle-to-site system boundary, as demonstrated in Table 4.

Our study, employing the contour crafting 3DP technique as the construction method, resulted in an embodied carbon value of 261.76 kg CO_2 eq/Unit function. In contrast, Abdalla et al. (2021) reported values of 608.55 kg CO_2 eq/Unit function for 3D printing method and 1154.2 kg CO_2 eq/Unit function for conventional construction method.

Table 4 Comparison analysis

Study	Embodied carbon (kg CO_2 eq/Unit function)
3D printing [Current study]	261.76
3D printing [11]	608.55
Conventional method [11]	1154.20

The comparison highlights that contour crafting resulted significantly lower embodied carbon emissions in comparison to conventional method and even when compared to similar 3D printing method documented in the literature.

5 Conclusion

This study introduces an innovative generic framework methodology designed for the comprehensive life cycle assessment (LCA) of concrete three-dimensional printing (3DP) processes within the architecture, engineering, and construction (AEC) industry, with a specific focus on evaluating their environmental impacts. A noteworthy departure from previous research, which often concentrated on specific life cycle phases, materials, or methods, this study fills a crucial gap by developing a generic framework on 3DP LCA pertaining to the AEC industry. The framework's effectiveness is demonstrated through a meticulously chosen case study involving a 2-storey residential villa with a plot area of 272 m^2 in the emirate of Sharjah, United Arab Emirates (UAE), a locale synonymous with extensive concrete utilization. The contour crafting 3D printing method is employed in the case study, utilizing a cradle-to-construction strategy to assess the environmental impact exclusively up to the completion of the construction phase.

Embarking on the case study, the analysis of embodied carbon emissions reveals that the contour crafting technique emits approximately 103,135 kg CO2. Notably, concrete mix emerges as the predominant contributor, accounting for 52% of the total equivalent concrete mix over the life cycle stages under consideration. This information provides a nuanced understanding of the specific environmental implications associated with the chosen 3D printing method, aiding in the broader comprehension of the technology's ecological footprint.

While the research makes significant strides in addressing the environmental impact assessment of 3D printing in the AEC industry, it acknowledges a primary limitation, which is the scarcity of relevant literature and comparative studies. This scarcity poses a challenge to gathering the requisite data needed for a more comprehensive analysis. To address this, our future research agenda encompasses a commitment to expanding the framework's application to encompass various concrete 3DP technologies, such as D-shape, and diverse building types, including commercial structures. By broadening the scope, we aim to enhance the generalizability of our findings and contribute to a more nuanced understanding of the environmental impacts associated with different 3DP technologies and building typologies.

In addition to addressing the data limitations, our future work emphasizes the exploration of mitigation measures to curtail the environmental footprint associated with 3D printing in the AEC industry. By identifying strategies to minimize adverse environmental impacts, we hope to provide actionable insights that can guide decision-makers in adopting more sustainable practices. This forward-looking approach aligns with our overarching goal of not only identifying environmental challenges but also actively contributing to solutions that promote sustainability within the AEC sector.

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