Environmental Assessment of large-Scale 3D Printing in Construction: A Comparative Study between Cob and Concrete

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Abstract

This paper explores the environmental impacts of large-scale 3D printing (3DP) construction in comparison to conventional construction methods using two different types of construction material: concrete and cob (a sustainable earth-based material). The study uses a standard Life Cycle Assessment (LCA) method, from cradle to site, to assess the environmental impacts of the construction materials and processes, with a focus on load-bearing walls in small/medium size houses. As expected, cob-based methods (conventional followed by 3DP) show lower overall environmental impacts and global warming potentials than the concrete- based methods. The study also shows that while the overall environmental impacts of 3DP concrete is higher than that of 3DP cob due to higher global warming potential, stratospheric ozone depletion and fine particulate matter formation, it has less impact on marine eutrophication, land use, and mineral resources scarcity. The environmental issues that remain to be overcome in relation to 3DP concrete is its high-cement content, while the issue in 3DP cob rises from the use of electricity for the 3D printing operation. The study indicates that the use of renewable energy resources and innovative material science can greatly increase the potentials of both 3DP cob and 3DP concrete respectively for future construction.

1. Introduction

In 2018, the International Energy Agency (IEA) reported that the average rate of growth of global energy consumption had increased almost two-fold since 2010. This high energy demand increased CO_2 emissions by 1.7% in 2018 alone, reaching a new record in its history (IEA, 2018). The building construction sector and its operations accounted for 40% of the CO_2 emissions and 36% of global fine energy use in 2018 (IEA and UNEP, 2018). At the same time, buildings play an important role in transitioning to a low-carbon economy

(Shrubsole et al., 2019). The drive to improve environmental conditions and reduce carbon emissions has led to innovations in technology and construction techniques (Shrubsole et al., 2019). Digital fabrication technologies in the manufacturing industry are also being adopted in architecture and construction (Craveiro et al., 2019). 3D printing technologies, in particular, have become a focus of attention in a number of diverse fields, including the construction sector (Wang et al. 2014; Soliman et al. 2015).

3D printing involves producing three dimensional objects by layering different materials (ASTM International, 2013). 3D printing has developed dramatically in recent years and can now be done using a range of materials (Agustí-juan et al., 2017). Where originally the use of 3D printing was restricted to the creation of physical models to present concepts to stakeholders; it is now being used to build entire buildings (Geneidy & Ismaeel, 2018). A milestone in the development of 3D printing technology took place when "Contour Crafting", a research project conducted at the University of Southern California, showed how layered extrusion technologies can work within large scale constructions (Khoshnevis et al., 2006).

The use of 3D printing in construction is gaining increased attention around the world. Several companies, such as Apis Cor, CyBe and Winsun, have upscaled technology intake over the past 5 years and have started tendering for 3D printed projects in Europe, Saudi Arabia, the United Arab Emirates and China (Apis-cor, 2019; CyBe, 2019; Winsun3d, 2019). In 2019, Apis Cor constructed the world's largest 3D Printed (3DP) building in the UAE for the Dubai Municipality. The building stands over an area of 640 square meters and has two-stories with an overall wall height of 9.5 meters. The walls were all 3D printed on site while the foundations and slabs were constructed conventionally (Apis-cor, 2019).

Although there have been numerous studies and many advancements in 3D printing of buildings, 3D printing applications in construction are still at an early stage and are still fairly limited in terms of project scale, materials, and the high cost of the technology (Wu et al., 2016; Berman, 2012). The other important aspect that remains insufficiently explored to date is the environmental impacts and the Life Cycle Assessment (LCA) of the 3DP technologies in construction (Veliz Reyes et al., 2018). There is, therefore, the need to investigate the environmental impact of 3D printed building design, materials, technology, regulations and codes (Dixit, 2019).

The Life Cycle Assessment (LCA) method, which is presented in the ISO 14040- 44: 2006 Standards (ISO 2006), is an assessment method of the environmental impacts of products and processes. LCA has been used in the construction sector for the last twenty years (Singh et al., 2011; Buyle et al., 2013). LCA methods can evaluate and optimise the construction processes by taking a comprehensive and systemic approach to environmental assessment (Tulevech et al., 2018). LCA in construction has two main approaches, depending on the required level of depth of assessment (Häfliger et al., 2017). The first approach involves a comprehensive level of detailing of the environmental impact of a building over its entire life cycle, including all the associated processes and materials (cradle to grave). The second approach assesses and compares only the environmental impact of the construction materials and/ or construction method (cradle to site). According to ISO14040, 2006, LCA involves four phases that work iteratively: The first phase is to define the goal and scope for launching the system boundaries and the quality criteria for the inventory data and functional unit. The second phase entails the inventory analysis (LCI), which focuses on the life cycle of the products in several steps. This phase deals with the production and collection of information on energy flows and physical material. The third phase is a life cycle impact assessment (LCIA), which uses the data collected from LCI and calculates their contribution to various environmental impact groups. The last phase is interpretation, which evaluates results to achieve conclusions, identifies important issues, gives recommendations, and describes limitations.

There are several impact assessment methods to calculate environmental performance, including CML, EDIP, ReCiPe, and TRACI (Cavalett et al., 2013) and each of these methods combines several impact indicators/ categories**.** The ReCiPe method, for instance, combines eighteen impact categories, as listed by Goedkoop et al. (2009), namely: global warming potential, ozone depletion potential, terrestrial acidification potential, freshwater eutrophication potential, marine eutrophication potential, human toxicity potential, photochemical oxidant formation potential, particulate matter formation potential, terrestrial ecotoxicity potential, freshwater ecotoxicity potential, marine ecotoxicity potential, ionising radiation potential, agricultural land occupation potential, urban land occupation potential, natural land transformation potential, water depletion potential, mineral depletion potential, and fossil depletion potential. Each impact category has its weight and significance on the environment. Product Environmental Footprint Category Rules Guidance (PEFCR Guidance) provide recommendations for the most relevant impact categories to current global environmental concerns (European Commission, 2017). These recommendations are based on normalised and weighted factors, representing the level of importance per category based on its impact on the environment.

To date, a limited number of studies have been conducted to assess the environmental opportunities of applying digital fabrication and 3DP methods in construction (Soto et al. 2018; Dixit 2019). Researchers have generally focused on the environmental impact at a small scale, for example, Kreiger and Pearce (2013), who studied the environmental benefits of distributing conventional and 3D printing of polymer products. A study conducted by Faludi et al. (2015) compared the environmental impacts of two types of additive manufacturing machines versus traditional numerical (CNC) milling machines and showed that there is a reduction in energy use and waste in additive manufacturing machines when compared to CNC milling machines.

Recently, Yao et al. (2019) compared 3D printing geo-polymer technology and the use of ordinary concrete in four scenarios using a Life Cycle Assessment (LCA) method. The study revealed that 3D printing technologies perform better environmentally and possibly lead to a reduction in waste when creating complex construction components. However, ordinary concrete performed environmentally better than 3D printed geo-polymer when it came to building simple walls. Prior to this, Kafara et al. (2017) conducted a comparative study of 3D printing manufacturing and conventional manufacturing of mould core making for carbon fiber reinforced polymer (CFRP) production. The results revealed that 3D printing manufacturing performed better on an environmental scale than conventional manufacturing. In recent years, researchers have started to explore 3D printing of earth-based materials, such as cob, as an eco-friendly substitute to 3D printed concrete (Perrot et al. 2018). It is claimed that 3D printing of earth materials can leverage the environmental potential of 3D printing techniques by reducing waste and the transportation and carbon footprint of the construction process (Gomaa et al., 2019; Veliz Reyes et al., 2018).

Concrete is one of the most used materials in conventional construction in the Middle East and Saudi Arabia (General Authority for Statistics, 2019). On the other hand, the Middle

East region, including Saudi Arabia, is rich with earth materials and Cob houses (Ibrahim, 2018; NICDP, 2020). Saudi Arabia's national development plan (Vision 2030) envisages adopting and using new technologies, such as 3D printing, with the aim of becoming a global investment powerhouse (Saudi Vision 2030, 2018). Saudi's government aims to increase the percentage of ownership of houses by 60% (Housing Program, 2019). The fast-growing building industry in Saudi Arabia is pushing the government towards the adoption of advanced construction methods that can meet the new development agenda. The increasing demand is expected to substantially increase energy consumption with consequent environmental implications (Asif et al., 2017). This makes it even more imperative to study the environmental impact of the building industry.

Hence, the main aim of this study is to compare the environmental impact of the 3D printing construction method with conventional construction methods using two different types of construction material: concrete and cob. Both materials are conventionally available worldwide with well-established knowledge of practice and historical performance. This approach is expected to provide a clearer understanding of the environmental implications of using 3D printing methods in construction, which should empower designers, project planners and stakeholders with the necessary data to make informed decisions regarding construction methods and materials. The study focuses on the construction market in the Middle East, particularly Saudi Arabia.

2. Methods and Materials

2.1. Life cycle assessment set up

The study used SimaPro 9.0.0.35 software (PRé 2019) to implement the LCA method. As recommended in ISO 14040 and 14044, the Ecoinvent v3.1 database was used because it is a compliant data source for studies and assessments. The ReCiPe Midpoint (H) v1.03 method for impact assessment was used as it provides a wide range of environmental categories, used in most scientific studies on LCA (Huijbregts et al., 2017; Agustí-Juan et al., 2017). For water use analysis, the study implemented the Available Water Remaining (AWARE) method, as recommended by the United Nations Environment Programme (UNEP/SETAC 2016). The chosen processes for the LCA of the constructed walls were raw material extraction, transport, material manufacturing, and the energy required for construction.

This study focuses on the most relevant impact categories, which are identified as all the impact categories that cumulatively contributed to at least 80% of the total environmental impacts (excluding toxicity related impact categories)(European-Commission 2017). The seven most relevant impact categories, as advised by PEFCR Guidance, are: 1) global warming; 2) stratospheric ozone depletion; 3) fine particulate matter formation; 4) marine eutrophication; 5) land use; 6) mineral resource scarcity; and 7) water use (AWARE). The latest normalisation and weighting factors for this study were obtained through the European Commission Platform on Life Cycle Assessment (European Commission, 2017; Sala et al., 2018; European, Commission 2019).

2.2. Study goal and scope

Given the limited information about 3D printed constructions, the LCA carried out for the purposes of this thesis is a cradle to site, which includes raw materials, transportations, and construction process on site. The using phase and demolishing phase are not included in this study. LCA is applied to assess and compare the environmental impacts of two different construction methods: 3D printing and conventional construction methods. The materials used in both methods are concrete and cob. The conventional concrete method commonly used in Saudi Arabia involves reinforced concrete structures (column and beam) and blockwork walls while the 3DP method involves solely the concrete mix. On the other hand, cob ingredients are the same in both conventional and 3DP methods, but with different ratios.

The functional units of each construction method are chosen to represent a section of an external load bearing wall in a one-storey house. All the units share the same standing area of $1m^2$, while the thicknesses vary to reflect the differences in the physical/structural properties of each method. It is important to note that, despite both cob and concrete are constructed using the same technology of 3D printing, each material has its own unique physical and structural characteristics. It is obvious that concrete has higher structural strength per unit area as compared to cob. Hence, the design of the wall section differs within the same structural function. Both Conventional and 3DP concrete require simpler wall design as compared to conventional and 3DP cob for the same wall unit in same building design. This means, when building a one-storey house, both concrete and cob walls will be designed to satisfy the same structural function.

The conventional method of building with cob requires a load bearing wall with a thickness that varies from 20 cm to 120 cm. An architect usually defines the thickness variation based on several factors, such as expected load, total wall height, and which part of the wall is being constructed (i.e. bottom or top of the wall). The most used thickness of straight cob walls (no tapering) is 62 cm on average. For tapered walls, this thickness varies from 120 cm at the bottom to 20 cm at the top (Hamard et al., 2016; Quagliarini et al., 2010). This study is based on straight cob walls with a thickness of 60 cm for use in a conventional cob functional unit.

The 3DP concrete wall was designed with a thickness of 40 cm, based on the walls used in a recent project in Saudi Arabia (CyBe, 2020). The 3DP cob was designed with a thickness of 60 cm similar to the standard used in straight cob walls and the thickness of similar walls constructed by researchers at Cardiff University and at 3D WASP (Veliz Reyes et al., 2018; 3D WASP, 2020). Both 3DP walls comprise an internal pattern filament (Figure 1).

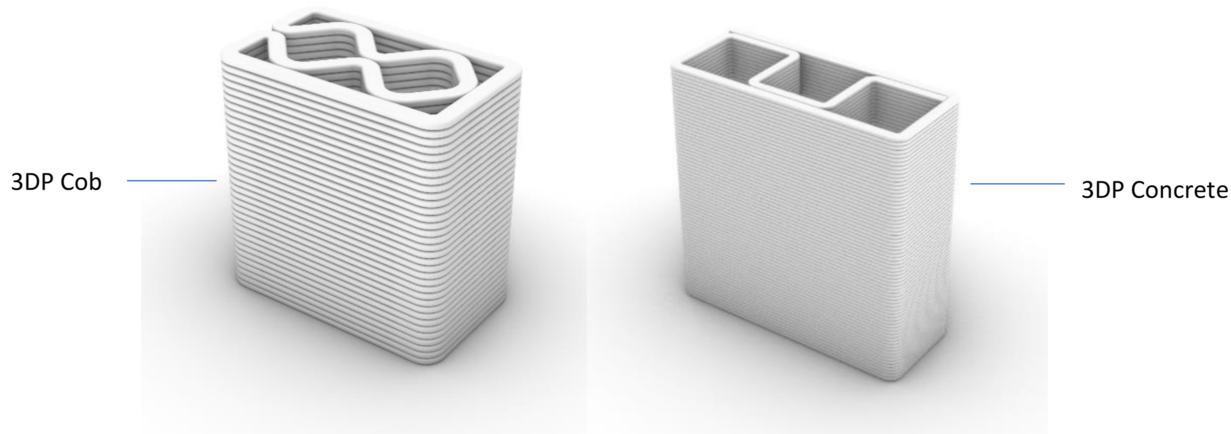

Figure 1. 3DP cob wall and 3DP concrete wall.

The selection of a comparable functional unit in a conventional concrete structure wall for this study requires a different approach, as the walls in this type of construction do not have uniform geometry (e.g. cube, parallelepiped). A structural “functional” wall unit in a concrete structure combines three components: columns, beams and blocks/ bricks (Figure 2). Hence, the study selected another transitional functional unit for the conventional concrete wall, i.e. 4 (L) x 3 (H) meters. This makes the standing area of this wall 12 m^2, which is 12 times the standing area of each of the other three functional units. Since the LCA comparison depends mainly on quantities, the calculated quantities in the 4 x 3 meter concrete wall were divided by 12 to represent the quantities in a 1 m^2 unit. Worth mentioning is the fact that it is possible to reverse this approach by upscaling the small functional units to 12m^2 walls. However, keeping the functional units as 1 m^2 will maintain a more generalised unit that will facilitate multiplication and reproduction of results.

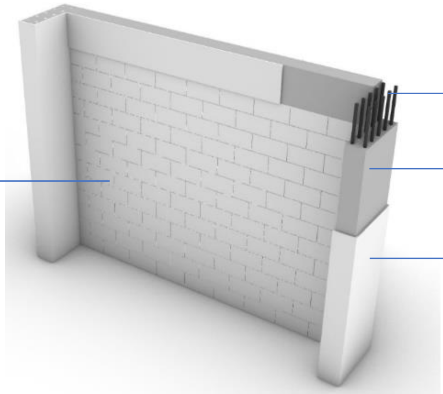

Figure 2. Conventional concrete construction wall.

Table 1. The specifications for each wall section per method.

Wall name	Method	Area m^2	Thickness	Type	Volume m^3
Conventional Concrete	Conventional	1	NA	solid	0.3[1]
Conventional Cob	Conventional	1	0.6	solid	0.6
3DP Concrete	3D printed	1	0.4	patterned	0.16
3DP Cob	3D printed	1	0.5	patterned	0.31

As shown in

Table *1*, there are differences in volume between the 3D printed versions and the conventional method. The reason for this is that the 3D printed walls are combined with inner gaps in their design by default, which is a beneficial characteristic of the 3D printing technology that enables a reduction in the amount of construction material needed and an increase in the thermal performance of the walls (Veliz Reyes et al., 2018; Gomaa et al., 2019).

[1] This volume includes concrete mix, framework, concrete block, reinforcement steel, and mortar.

2.3. Electricity Consumption Calculation

2.3.1. Calculating the Electricity Consumption for 3D Printed Cob and Concrete

The electricity consumed for the robotic arm operation during the construction process can be estimated either practically or mathematically. The practical measure of power consumption requires the use of electricity/power meters that only read the power source for the digital fabrication tools being used (i.e. in this case a robotic arm) or, if the tools are battery powered, a calculation of the number of full charges needed to finish the construction process. The mathematical method to estimate the electricity consumption depends on knowing the power ratings in Kilowatts (kWh) of the fabrication tools and the time required to complete the fabrication process. The total electricity consumption can then be obtained using the following equation:

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

The fabrication tool used in the study is a KUKA KR60 HA robotic arm. This robot has a direct supply line of electricity but does not have an electricity meter. Therefore, the study used the mathematical estimation of power consumption. The robot operates 3D printing tasks with a payload of approximately 30 kg, and it has 6 motors on each of its axes; the motors have a collective power rating of 16.8 kW when working on maximum capacity, with 60 kg payload on the robot head. The motors are assumed to work initially at 50% of their full capacity, which is 8.4 kW. A sensitivity analysis has been conducted by examining another scenario where the robot runs on its full capacity.

To calculate the required time for the 3D printing process, two factors need to be defined: firstly, the 3D printing speed; and secondly, the perimeter length of the design pattern/path line for the wall, inclusive of all the layers. The operation time can be calculated by dividing the perimeter length over the 3D printing speed. The printing speed differs between 3DP in cob and a 3DP in concrete because of the different properties of the materials. The printing speed for 3DP cob was set at 0.05 m/sec. This speed was found to be appropriate for cob printing based on several tests that took place at Cardiff University and the findings of Veliz Reyes et al. (2018). The 3DP concrete printing speed was set at 0.25 m/sec (BESIX, 2019).

The length of the perimeter/path line in 3D printing could be defined as the total length of all the layers that construct the wall unit, which equals the perimeter of a single layer multiplied by the number of layers. This study uses inner patterns for the 3DP walls as adopted in the industry. The selected pattern for the 3DP cob was inspired by 3DP WASP prototypes (3D-WASP), while the chosen pattern for the 3DP concrete was supplied by the CyBe project in Saudi Arabia (CyBe 2020)(Figure 3). The length of the total path line for the 3DP cob is 146.3 m and for the 3DP concrete 412 m. This noticeable difference in path line length between cob and concrete is due to the difference in the 3D printing settings. The printing layer height in the 3DP cob is 30 mm, while in the 3DP concrete it is 10 mm. Hence, more layers are required for the 3DP concrete to achieve the same required 1.0 m height wall. Increased number of layers means a longer total path line. By applying the previous calculations, the electricity consumption was found to be 6.8 kWh for 3DP cob and 3.9 kWh for 3DP concrete.

Figure 3. CyBe 3DP concrete pattern (left), 3D WASP 3DP cob pattern (right).

2.3.2. Electricity consumption for Conventional Cob and Concrete

In conventional constructions, the work is undertaken by manual labour. Nevertheless, in the environmental analysis, the energy requirements and emissions associated with human life are not counted usually (Agustí-juan et al., 2017). A study conducted by Alcott (2012) calculated the human factor, but the results showed that the impact was insignificant. Therefore, human factor is not included in in this study, that is, this study does not include the energy consumption to manufacture conventional concrete because all the manufacturing processes were done manually.

2.4. Material Characterisation

2.4.1. Cob

Weismann and Bryce (2006) suggested a water to subsoil ratio of one part water to every four parts of soil. This converts to 20kg of water per each 80kg of subsoil by weight (20: 80 %). The recommended amount of straw to be included in the mix is 2% of the weight of the subsoil and water mix. A comprehensive systematic review by Hamard et al. (2016) affirmed the proportions of the cob mixture (78% subsoil, 20% water and 2% fibre i.e. straw). Hamard et al. (2016) also stated that the subsoil formula itself is 15–25% clay to 75–85% aggregate/sand. Similarly, Harrison (1999) recommended a subsoil formula of 20% clay to 80% aggregate/sand.

However, as cob is conventionally mixed in a near dry state due to the low water ratio, the commonly used proportions of water to subsoil do not fit the purpose of the 3D printing technique. The 3D printing technique involves a material extrusion process through tubes and/or hoses; therefore, less viscous material is always preferred to reduce the amount of friction inside the system, which then reduces the loads on the motors. Two comprehensive studies on 3DP cob have recommended a new cob mix that has reduced viscosity. Based on a number of 3D printing tests, the water content in the 3DP cob mixture was increased to 23-25%, while the amount of straw was fixed at 2% (Gomaa et al., 2019) (Table 2).

Table 2.The components of 3DP and conventional cob.

	Subsoil		Water		Straw		Total (kg)
	%	Kg	%	Kg	%	Kg	
Cob conventional wall	78.0	748.8	20.0	192	2.0	19.2	960
Cob 3D printed wall	73.0	392.6	25.0	134.4	2.0	10.8	537.8

2.4.2. Concrete

3DP concrete is a mix of cement, fly ash, silica fume, sand, water, superplasticiser, and fibre (Le et al., 2012; Agustí-juan et al., 2017; Nerella et al., 2016; Anell 2015). Each of the previously cited studies suggested different ratios of material in the 3D printed concrete mix (Table 3). An extensive review of the literature revealed that Le et al. (2012) had carried out comprehensive testing of several 3DP concrete mixes to define which had the best workability and usability. Other studies used Le et al. (2012) as a main starting point to develop their new mixes (such as Labonnote et al., 2016; Ngo et al., 2018; Buswell et al., 2018; Wolfs 2015; Paul et al., 2018; Malaeb et al., 2015). Hence, this study conducted the LCA on the concrete mix recommended by Le et al. (2012). However, to further explore the differences in the environmental impacts of the 3DP concrete mixes, two more concrete mixes, taken from Nerella et al. (2016) and Anell (2015), will be used in the sensitivity analysis section.

This study used the 35MPa conventional concrete type and column size 60X20 cm^2 with 8 Ø 16 mm steel rods. The beam size was 40X20 cm^2 with 6 Ø 16 mm steel rods, each concrete block was 40 cm x 20 cm x 20 cm, and the formwork was plywood. Plywood sheets have a thickness of 15 mm and are assumed to be used twice (one time per each side). All of the reinforced concrete properties used in the conventional wall were taken from the National Committee for the Saudi Building Code (Table 4).

Table 3. Different 3DP concrete mixes ingredients and their densities based on previous studies.

	(Nerella et al. 2016)		(Le et al. 2012b)		(Anell 2015)		(AgustíJuan 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	

Table 4. The construction components of the conventional concrete method.

Concrete Conventional Wall	Percentage	Kg
Concrete blocks (main body)	50%	112.6
Formwork (wood)	16%	6.5
Reinforcement Steel	2%	12.3
Concrete mix	30%	206.1
Mortar	2%	12.5

3. Results and Discussion

This section discusses the results of the study in three steps. First, the overall outcome of the study, that is, the comparison of the four types of walls in terms of their environmental impacts. This step will also include a description of the results pertaining to the different properties of each material. The second step explores the breakdown of the impact of each wall type. This aim of this breakdown is to determine which material and/or process has the highest environmental impact within each wall type. Having defined the highest contributors, the third step will be to analyse the sensitivity of each contributor and describe the changes in the environmental impact.

The produced analyses in Simapro were initially in the form of characterised values that show the relative difference in the environmental performance between the four wall types, as can be seen in Figure 4. In order to obtain a holistic overview of the whole impact of the products, the characterised results must be normalised and weighted using special factors as indicated in the PEFCR guidance (European-Commission 2017). Normalised and weighted results can then be used as a real representation of the performance in all the impact categories collectively. For example, in Table 5, the characterised values were normalised using the normalisation factor (NF/person), then weighted using the weighting factor (WF/person) to produce the overall improvement in performance per wall type in all the impact categories combined, all as compared to the conventional concrete wall.

3.1. Primary comparison

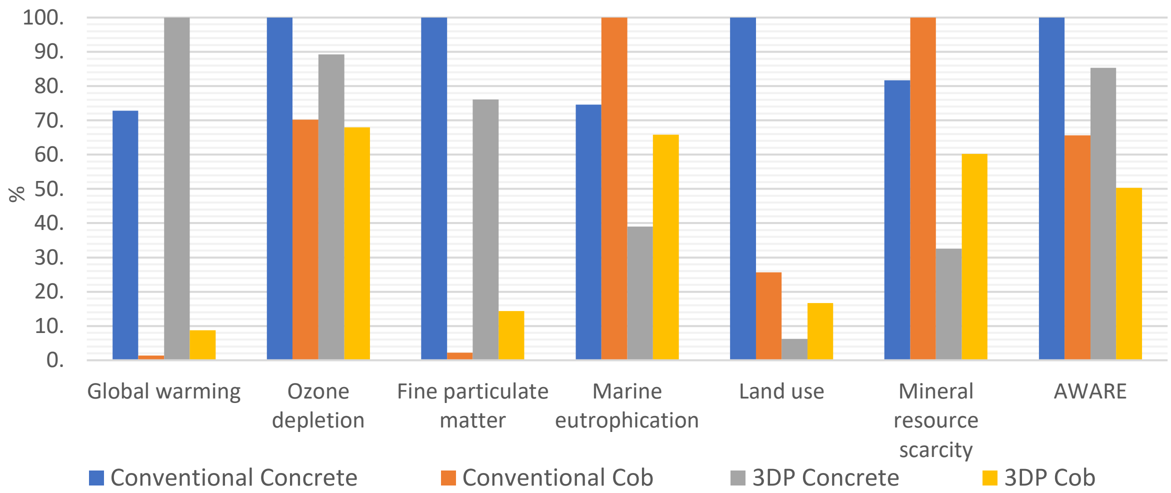

Figure 4. Chart shows the characterised overall outcome of comparing the four types of walls.

Table 5. Percentage of improvement in environmental performance of the wall types as compared to conventional concrete method. (NF: Normalisation factor; WF: Weighting Factor)

Impact categories	NF/person	WF/person	Conv. Cob	3DP Conc.	3DP Cob
Global warming	8095.53	22.19	98.2%	-27.2%	87.9%
Stratospheric ozone depletion	5.37E-2	6.75	29.8%	10.7%	32.0%
Particulate matter	5.95E-4	9.54	97.8%	23.9%	85.7%

Marine eutrophication	19.545	3.12	-34.0%	47.7%	11.7%
Land use	81.94E+4	8.42	74.3%	93.8%	83.3%
Mineral resource scarcity	6.36E-2	8.08	-18.3%	60.1%	26.4%
AWARE (water depletion)	11468.7	9.03	34.3%	14.7%	49.7%
Overall improvement	--	--	96%	24%	85%

The results generally align with the results of several other studies (including Agustí-juan et al., 2017; Kafara et al., 2017) which claimed better environmental performance for 3DP technologies when compared to conventional concrete construction. The novel added factor in this study is the introduction of cob as an alternative material in both the conventional and the 3D printing methods. The conventional concrete wall recorded the highest overall environmental impact out of all the other three walls. In addition, the 3DP concrete wall achieved a collective 24% improvement in all the seven relevant impact categories combined when compared to conventional concrete. However, in the global warming category, 3DP concrete performed 27.2% worse than conventional concrete. Unsurprisingly, the 3DP cob showed better environmental performance as compared to the concrete-based walls, with an overall improvement of 85% over the conventional concrete wall and 87.9% improvement in the global warming category only (Figure 4 and Table 5).

The study initially included the conventional cob wall as a base line as it was anticipated that this will yield the most efficient environmental performance. This was a correct assumption on a collective scale; interestingly, however, both the 3DP cob and the 3DP concrete performed better in comparison with the conventional cob wall in several impact categories, such as marine eutrophication, land use and mineral resources scarcity. These three categories are heavily related to the use of straw and subsoil, which are found in large amounts in conventional cob walls. However, conventional concrete performed better than conventional cob in the mineral resource scarcity category, again due to the huge presence of subsoil in conventional cob (Figure 4 and Table 5).

When focusing on concrete-based walls, the results revealed that 3DP concrete has an overall improvement in all categories collectively with 24%, except for the global warming category (European Commission, 2017). This is mainly due to the use of concrete and fly ash. Additionally, the reason for the poor performance of conventional concrete in the other impact categories is the presence of reinforcing steel and concrete which contribute highly to CO_2 emissions (Habert et al., 2013). These results could change if the comparisons were done on the basis of a whole building, including all structural elements, because 3D printing technology produces almost zero waste (Xia and Sanjayan, 2016)(Figure 5 and Table 6).

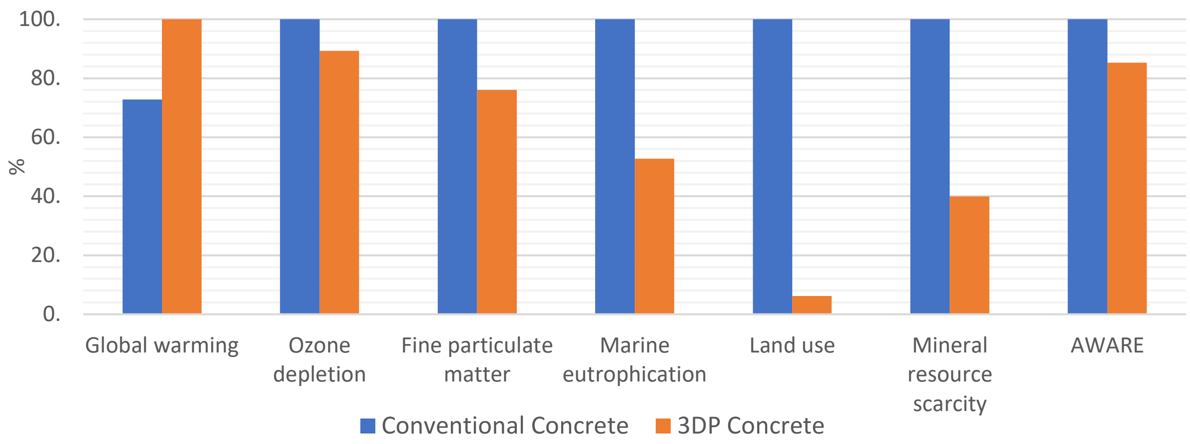

Figure 5. Comparison between 1 m^2 3DP Concrete wall with 1 m^2 Conventional Concrete.

Table 6. Percentage of improvement between 3DP Concrete and Conventional Concrete.

	Conventional Concrete	3DP Concrete
Global Warming	27.2%	--
Stratospheric Ozone Depletion	--	11%
Fine Particulate Matter	--	24%
Marine Eutrophication	--	47%
Land Use	--	94%
Mineral Resource Scarcity	--	60%
Aware	--	15%
Overall Improvement	--	24.0%

On the other hand, despite the outperformance of 3DP cob over conventional cob in five of the seven impact categories, conventional cob has shown a much higher overall performance, with 83% improvement over 3DP cob (Figure 6 and Table 7). This is clearly down to the good performance of conventional cob in two of the most important and highly weighted impact categories: global warming and fine particulate matter formation (European Commission, 2017). It is also due to the high use of electricity in 3DP construction, which severely affects both global warming and fine particulate matter formation. The breakdown of both materials will be given in the following section.

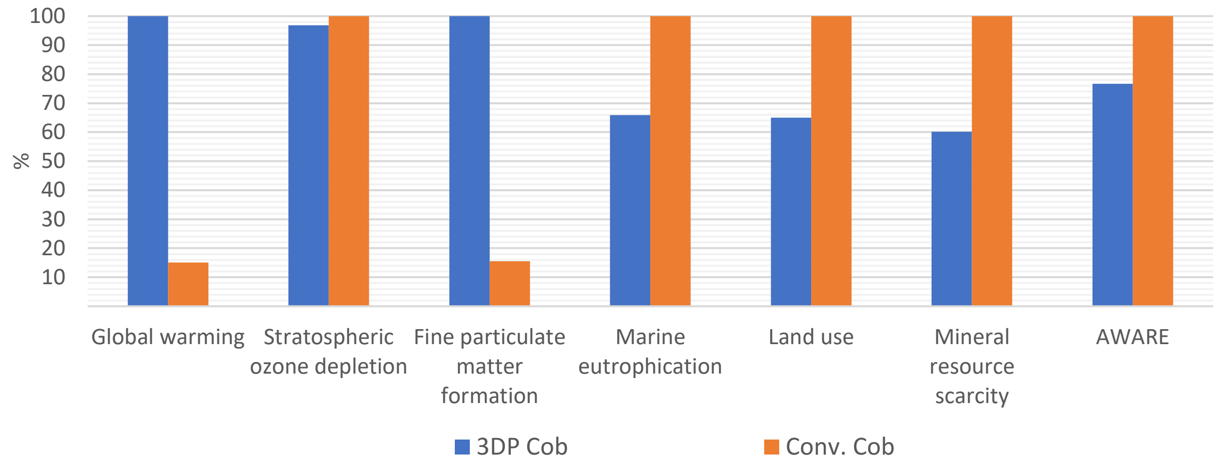

Figure 6. Comparison between 1 m^2 3DP Cob wall with 1 m^2 conventional Cob.

Table 7. Percentage of improvement between 3D Cob and conventional Cob.

	Percentage of Improvement	
	3DP Cob	Conventional Cob
Global Warming	--	85%
Stratospheric Ozone Depletion	3%	
Fine Particulate Matter	--	84%
Marine Eutrophication	34%	
Land Use	35%	--
Mineral Resource Scarcity	40%	
Aware	23%	--
Overall improvement		83%

Since the focus of this study was 3DP technologies, a focused comparison on 3DP concrete and 3DP cob is provided in Figure 7 below. As seen in Table 8, the environmental performance of 3DP cob is 80.0% better than 3DP concrete in the seven impact categories. The graph below (Figure 5) shows that 3DP cob achieved a better performance in global warming, stratospheric ozone depletion, and fine particulate matter formation, while 3DP concrete performed better in marine eutrophication, land use, and mineral resources scarcity.

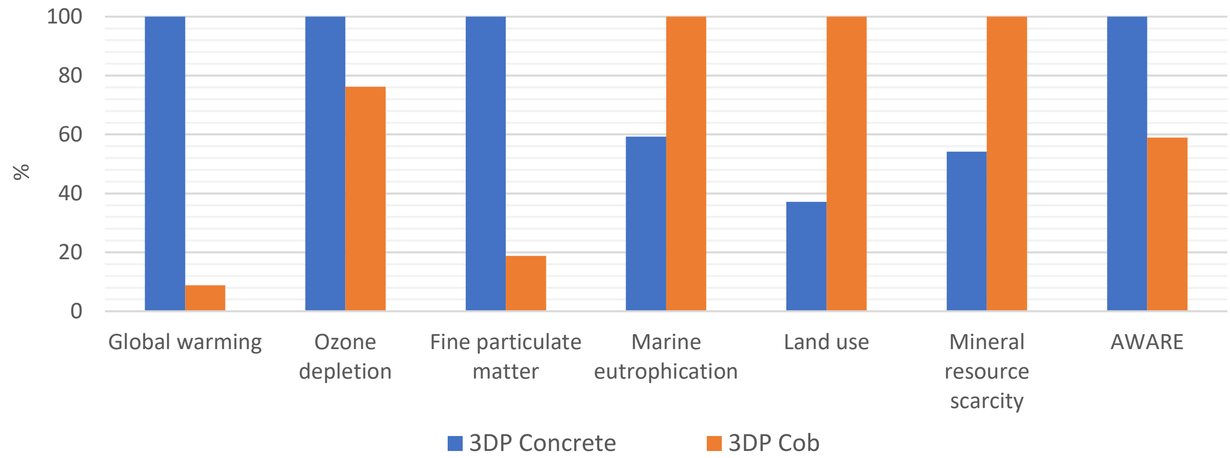

Figure 7. Comparing 1 m^2 3DP Concrete with 1 m^2 3DP Cob.

Table 8. Comparison of the environmental performance between 3DP Cob and 3DP Concrete.

	3DP Concrete	3DP Cob
Global Warming	--	91%
Stratospheric Ozone Depletion	--	24%
Fine Particulate Matter Formation	--	81%
Marine Eutrophication	41%	--
Land Use	63%	--
Mineral Resource Scarcity	46%	--
Aware	--	41%
Overall improvement	--	80.0%

3.2. The breakdown of impacts

For a deeper understanding of the results, each wall type was analysed separately through a breakdown of ingredients in order to identify the impact in relation to each sub-material. Also, the overall contribution of all categories will be analysed with a focus on global warming as the most important impact category. The results were normalised and weighted to give a better understanding of each impact category.

With regards to conventional concrete, it was found that 49% of the environmental impact was due to the reinforcing steel which scored the highest contribution out of all the categories, except land use where plywood scored the highest. Furthermore, concrete scores as the second highest contributor with an overall 19% contribution in all categories (Figure 8). This finding obviously puts 3DP techniques at an advantage as it does not require the use of formwork and reinforced steel (CyBe 2020). However, the high presence of cement in the 3DP concrete wall reduced its environmental performance, especially in the global warming impact category, where it obtained the worst environmental performance scores out of the three types of wall. The impact breakdown of 3DP concrete shows that cement and fly ash are collectively responsible for 70.8% of the environmental impact and obtained the highest contribution scores out of all the categories. Transportation achieved the next highest score with 12.8% contribution in all the categories (Figure 9).

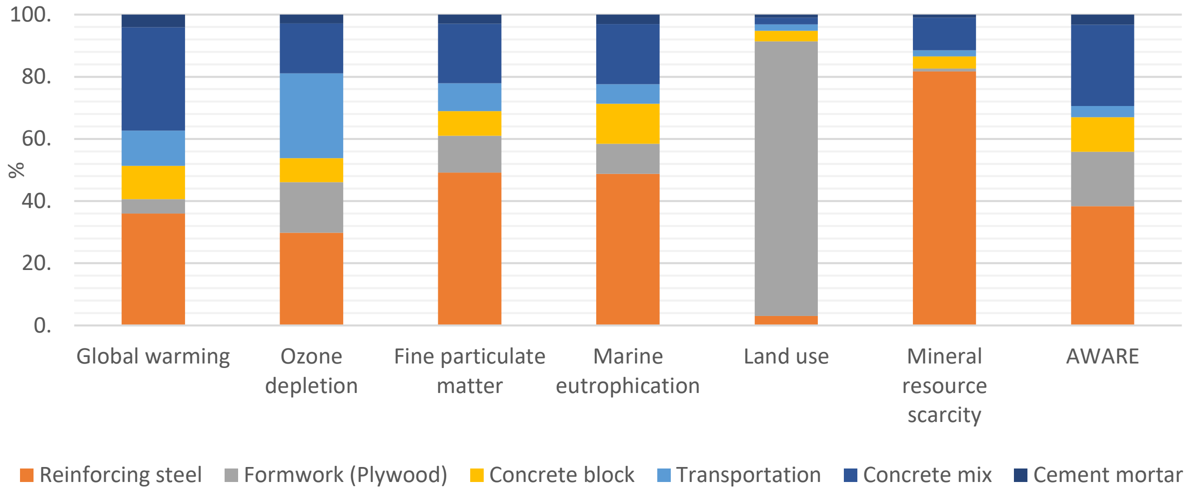

Figure 8. Breakdown analysis of 1 m^2 wall of Conventional Concrete type.

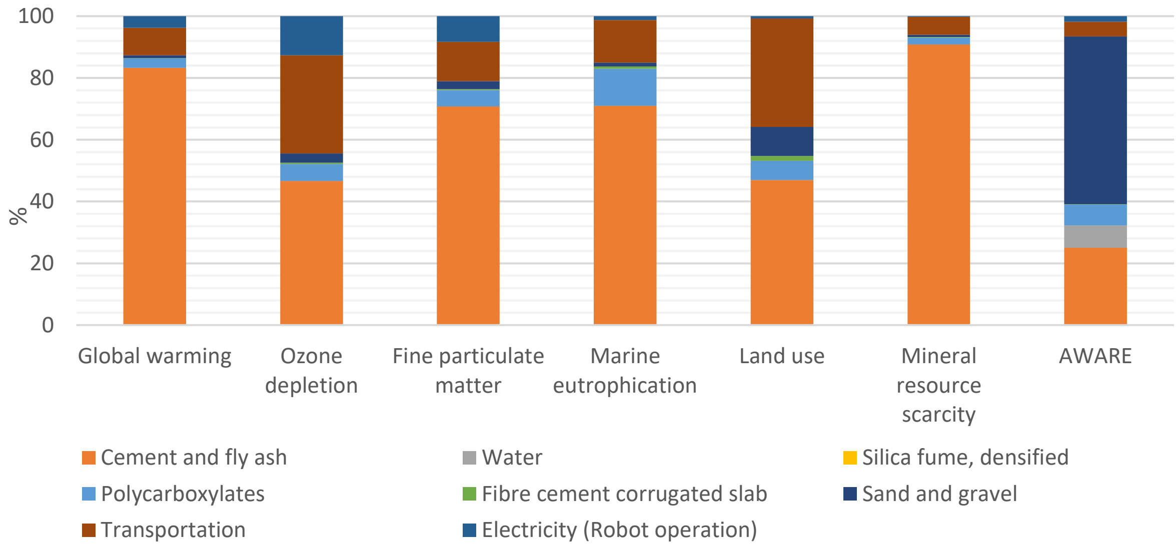

Figure 9. Breakdown analysis of 1m^2 wall of 3DP Concrete.

In conventional cob construction, straw contributes 68% of the overall impact across all the categories, except mineral resource scarcity, where subsoil contributed the highest score (Figure 10). On the other hand, the electricity used in 3DP cob, mainly used in the operation of the robotic arm, contributed 83% of the impact across all the categories, followed by straw with an overall score of 7% (Figure 11). Considering the very low ratio of straw (2%) in the cob mixture, it can be concluded that straw has a significant effect on overall environmental performance. In addition, 3DP cob was proven to have the best collective environmental performance, even when compared to conventional cob. This is due to the massive reduction in the quantity of material and weights used in 3DP cob in comparison with conventional cob due to the integration of voids in the internal structures and the minimal amount of material used in the wall volume.

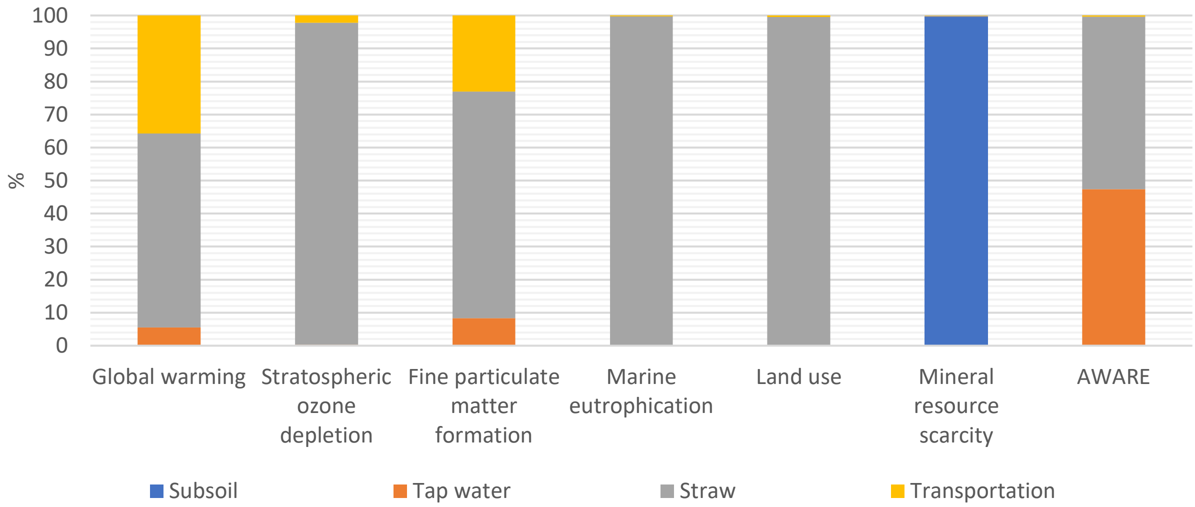

Figure 10. Breakdown analysis of 1m² wall of Conventional Cob.

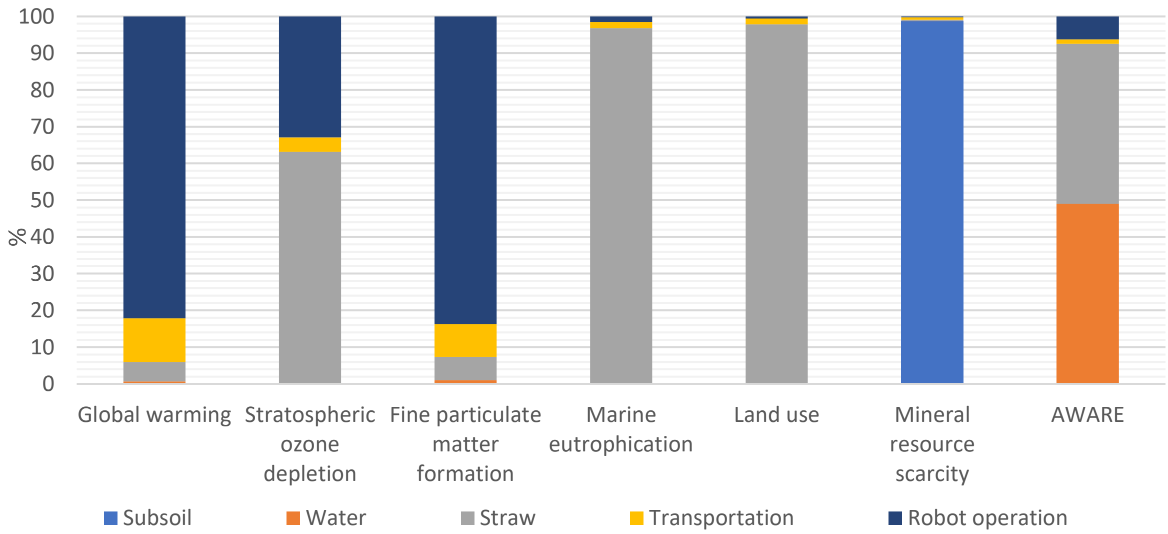

Figure 11. Breakdown analysis of 1m² wall of 3DP Cob.

3.3. Sensitivity analysis

Based on the previous observations, it is important to test the sensitivity of some materials that were identified to have a large environmental impact and explore how this impact can be improved or reduced. The sensitivity analysis for this study was carried out on the basis of three scenarios: (1) changing the percentage of steel reinforcement in conventional concrete; (2) changing the 3DP concrete mix; and (3) changing the robotic operation payload and geographical location. Conventional cob was excluded from the sensitivity analysis, as it had a significantly better environmental performance than all the other three types. Moreover, there is no demand for conventional cob for construction on the modern construction market.

3.3.1. Conventional concrete

As mentioned earlier, steel contributed the most to the environmental impact of conventional concrete. The quantity of steel used in the wall was originally calculated based on a reinforced 600x200 mm^2 column and 400x200 mm^2 beam which are used in a regular two-storey building. The amount of steel reinforcement and concrete were then reduced by nearly 20% and 22% respectively, to represent a smaller column of 400x200 mm^2 that can be used in a one-storey building, to mimic the walls that were used for the 3DP houses. This reduction in steel and concrete improved the performance of conventional concrete by an overall 17% and 16% in the global warming category when compared to the original concrete wall (Figure 12).

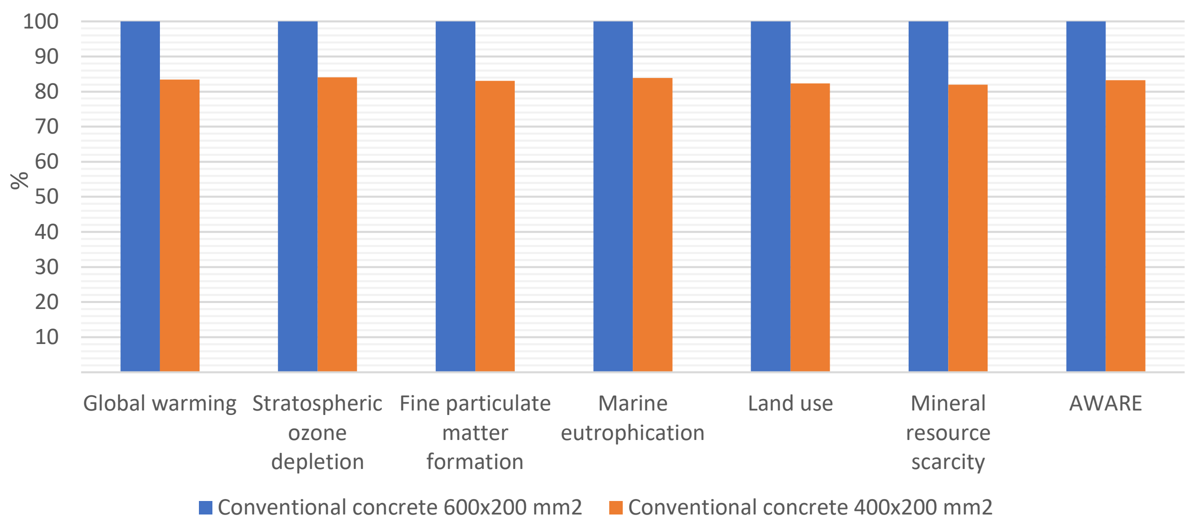

Figure 12. Comparing main Conventional Concrete wall to the reduced steel and concrete version.

3.3.2. 3DP concrete

As mentioned earlier, this study explored two more concrete mixes taken from Nerella et al. (2016) and Anell (2015) to better understand the variations in the environmental performance associated with changing mix ratios of the cement, fly ash and sand. The results demonstrated that there is no specific component to focus on, as each recipe has a different proportion of components (

Table 9). However, as shown, reducing cement and fly ash in the mix does not necessarily guarantee an improvement in the environmental performance of the 3DP concrete (

Table 9). It was observed that the reduction in cement and fly ash ratios in the 3DP concrete mix is usually accompanied by an increase in the sand and aggregate ratios, which then increases the overall quantities of material and consequently increases the environmental impacts of transportation. Therefore, it is concluded that it is important to analyse the main components of the 3DP concrete mix holistically.

It was found that, generally, all the three 3DP concrete mixes performed environmentally better than the conventional concrete wall, by 60.4%, 52.7% and 53.7% for the Nerella et al. (2016) mix, the Le et al. mix (2012) and the Anell mix (2015) respectively. However, the Nerella et al. (2016) mix had the lowest impact on global warming and all the categories when compared to the other mixes and conventional concrete (Table 10 and Figure 13). This may be an indicator that recently developed mixes can have the potential of performing better environmentally.

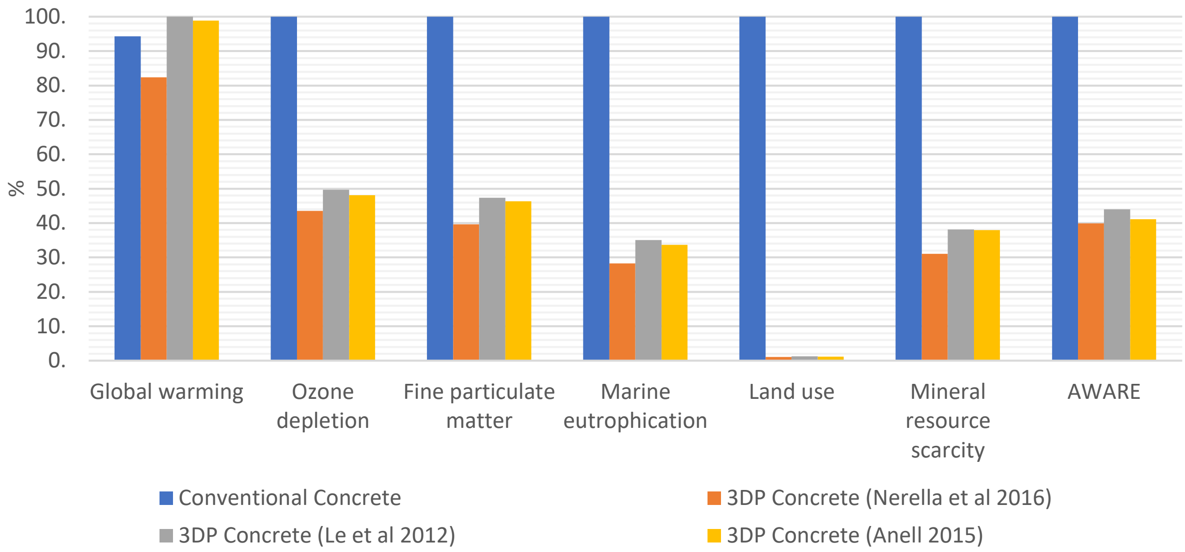

Figure 13. Comparison of the three 3DP mixes to conventional concrete wall mix.

Table 9. The percentage breakdown of contribution towards the environmental impacts for each component in the three 3DP concrete mixes.

	Cement and fly ash	Water	Polycarboxylates	Fibre cement	Sand and gravel	Transportation	Electricity (Robot operation)
(Le et al. 2012b)	71%	0.05%	5%	0.3%	2.6%	13%	8.3%
(Anell 2015)	72.5%	0.05%	4%	0.3%	2.4%	12.50%	8.5%
(Nerella et al. 2016)	68%	0.04%	4%	0.0%	3%	15%	10%

Table 10. The percentage of overall improvement in environmental performance of 3dP concrete mixes as compared to conventional concrete method.

	3DP Conc (Nerella et al. 2016)	3DP Conc. (Anell 2015)	3DP Conc (Le et al. 2012b)
Global warming	13%	- 4.6%	- 5.7%
Overall categories	60.4%	53.7%	52.7%

3.3.3. 3DP cob

A few changes were made in the robotic operation concerning electricity consumption and location. Firstly, the robotic operation capacity was changed from 50% to 100%. This means that the payload was changed from 8.4 kW to16.8 kW. This change led to double the amount of electricity consumption that deteriorated the performance of 3DP cob by 55% in both overall and global warming levels (Figure 14).

The impact of changing the geographical location from Saudi Arabia to Australia was also tested. The electricity in Saudi Arabia is totally produced from non-renewable energy resources (ERCA, 2018), while 19% of electricity generation in Australia comes from renewable energy sources (DEE, 2019). This study chose the state of South Australia (SA) as a case study for this sensitivity analysis as more than 50% of its electricity comes from renewable sources (DEE, 2019). Altering the location from Saudi Arabia to South Australia resulted in an improvement of the environmental performance by 52% overall and 36% in the global warming category (Figure 15).

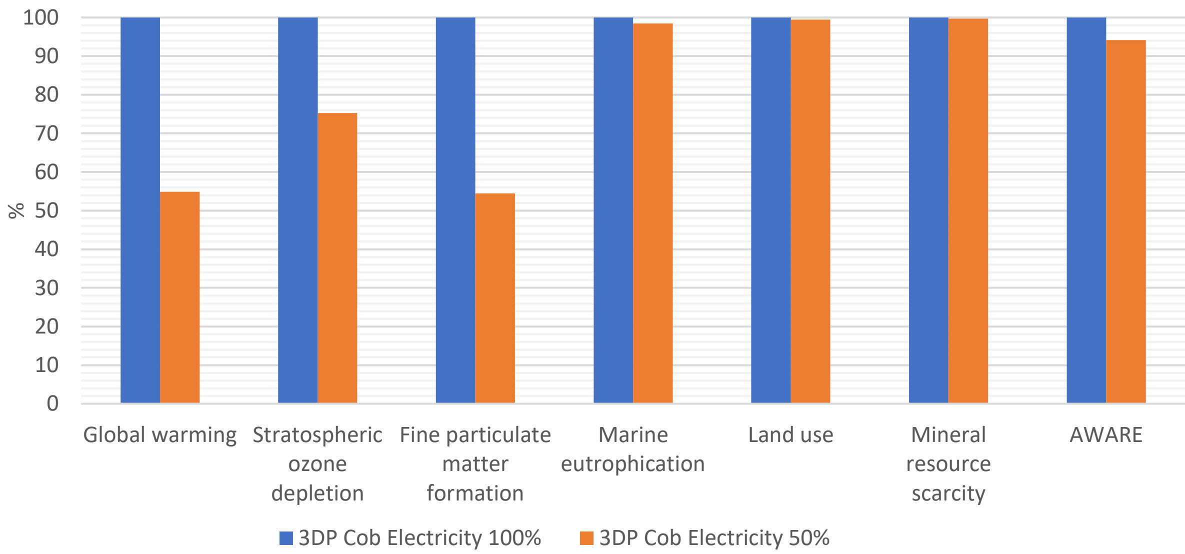

Figure 14. Comparing 3DP Cob 50% Electricity with 100% Electricity.

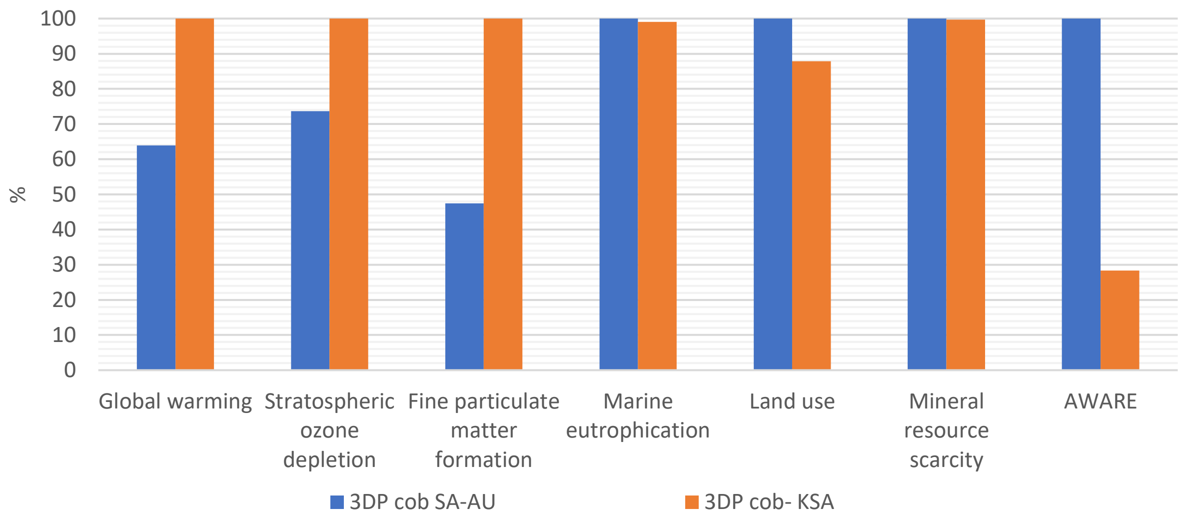

Figure 15. Comparison of 3DP Cob method in South Australia to 3DP Cob in Saudi Arabia.

4. Conclusion

Digital fabrication technologies have recently been adopted in architectural applications and constructions; however, the environmental impacts of such approaches have not been thoroughly investigated. This study compared the environmental impacts of constructing a wall using 3D printing construction methods with the impact of conventional construction methods. Four different types of materials were tested: conventional concrete, conventional cob, 3D printed (3DP) concrete and 3DP cob.

The study had the following results:

1. Conventional cob has the least overall environmental impact and global warming potential, followed by 3DP cob. As expected, conventional concrete had the, highest environmental impact in all categories except global warming.
2. While 3DP concrete had a lesser overall environmental impact (by more than 50%) than conventional concrete, the performance of 3DP cob is still better than 3DP concrete due to its lesser global warming potential, stratospheric ozone depletion and fine particulate matter formation.
3. However, while the overall environmental impact of 3DP concrete is more than that of 3DP cob, it has less impact on marine eutrophication, land use, and mineral resources scarcity.
4. A detailed analysis shows that the high environmental impact of conventional concrete construction is mainly due to the use of reinforcing steel (49% contribution) and concrete (19%).
5. The absence of reinforcing steel bars in 3DP concrete is the main reason for its better environmental performance when compared to the performance of conventional concrete.
6. While conventional cob has a better environmental performance than the other three construction methods, the high content of straw in conventional cob contributes to

its overall environmental impact while the use of subsoil contributes to mineral resource scarcity.

7. The consumption of electricity to operate the robotic arm in 3DP cob contributes to 83% of its overall environmental impact, while the very low straw content in the 3DP cob mixture contributes to its low environmental impact.

These results suggest that the environmental impact of conventional concrete is mostly due to its steel reinforcing bars as well as the concrete used. Changing the amount of steel reinforcement and concrete (but keeping it to the standards required for a one-story building) would reduce the environmental impact of conventional concrete. The environmental impact of 3DP concrete is mainly depending the ratio of the components of the mix, hence in the future modified mixes can reduce further the environmental impact of 3DP concrete.

On the other hand, the environmental performance of 3DP cob is not as affected by the material used as it is by the amount of electricity used to operate the robotic arm. Using renewable energy sources to generate electricity for the robotic operations would significantly reduce the environmental impacts of 3DP cob. The current global trends are moving towards renewable sources of energy (REN21 2019). Moreover, 3DP cob can generate complex shapes to meet the evolving demands of contemporary construction, which is difficult to achieve manually using conventional cob. In addition, 3DP facilitates modifications, repetitions, and maintenance if needed. However, 3DP cob still suffers some major limitations in terms of structural strength and productivity of the construction process as compared to 3DP concrete and other conventional construction methods. In the context of the limited available information regarding 3DP construction, this study aims to inspire researchers to further investigate 3DP construction and assess its performance from cradle to grave.

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