3D concrete printing for sustainable and economical construction

Citation for published version:
Batikha, M, Jotangia, R, Baaj, MY & Mousleh, I 2022, '3D concrete printing for sustainable and economical construction: A comparative study', *Automation in Construction*, vol. 134, 104087.
https://doi.org/10.1016/j.autcon.2021.104087

Digital Object Identifier (DOI):
10.1016/j.autcon.2021.104087

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
Automation in Construction

3D concrete printing for sustainable and economical construction: a comparative study

Mustafa Batikha[a,*], Rahul Jotangia[a], Mohamad Yasser Baaj[b], Ibrahim Mousleh[c]

[a]*School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Dubai, UAE*

[b] *Vice President of DuBox and CEO of B3G Engineering Services, Dubai, UAE*

[c] *Technical support engineer, Équipement Boni , Groupe SJM, Québec, Canada*

***Corresponding Author:** Mustafa Batikha, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Dubai campus, Dubai, UAE; email: m.batikha@hw.ac.uk, Tel.: +971 567088649.*

Abstract: Literature about 3D Concrete Printing (3DCP) examined small-printed elements or structures, while the data available about printed buildings are from the market. Therefore, there is no robust answer regarding 3DCP efficiency compared to other construction methods. In this research, a two-storey building was designed using five construction methods: 3DCP, prefabricated modular construction, cast-in-situ reinforced concrete, cold-formed steel and hot-rolled steel. The aim is to compare 3DCP to other construction techniques in terms of the construction duration, cost and CO_2 emissions. This study shows that excluding prefabricated modular concrete, 3DCP reduces the construction duration by about 95%. 3DCP also offers the greatest cost savings and behaves similarly to cold-formed steel to produce approximately 32% less CO_2 emissions. Thus, this work provides a necessary outlook on the current viability of 3DCP to relevant stakeholders and industry professionals and inspires future research on 3DCP as an economical and sustainable construction solution.

Keywords: 3D concrete printing; modular precast; cast-in-situ reinforced concrete; cold-formed steel; hot-rolled steel; cost analysis; construction duration; sustainability.

1. Introduction

It is well-known that the global population growth demands continuous expansion from the construction industry. It is expected that the world’s population will grow to 9.7 billion in 2050, with an average population growth rate of 0.84 % per year from 2010-2050 [1]. This population growth creates a greater demand for residential housing, offices, healthcare facilities and schools, through which the global construction industry is anticipated to record a Compound Annual Growth Rate (CAGR) of 5.7% to reach about USD 12 trillion by 2024 [2, 3]. The global residential construction industry has registered a CAGR increase of 6.0% in the last four years from 2015-2019 [2]. However, governments are currently under immense pressure due to the lack of affordable housing, considering that it is predicted that 68% of the world’s population will be city occupants by 2050 [4]. For example, Elkaftangui and Mohamed [5] highlighted that in the case of the United Arab Emirates (UAE), only 22% of the residential units are affordable for middle-income Emirati households, which represent about 40% of the total UAE population. Therefore, the UAE government has taken the initiative to launch the Emirates Development Bank (EDB), with AED 10 billion of authorized capital, to meet the UAE's vision of delivering 30,000 high-quality affordable homes by 2021 [5].

The construction industry's development gives rise to the issues of environmental degradation and the health and safety of the construction technique, as well as other factors like construction cost and duration. Today, the world of construction is dominated by in-situ Reinforced Concrete (RC) construction. Although there are other construction methods like Hot Rolled Steel (HRS), Cold-Formed Steel (CFS) or Prefabricated Concrete Construction (PCC), the heavy dependence on RC is due to the mass availability and low cost of the material constituents, the requirement for less-skilled labour, its fire and weather resistance and economical maintenance along with proven efficiency in terms of strength and slow rate of deterioration. Nevertheless, in-situ RC construction produces too much construction waste. Mália et al. [6] estimated that new in-situ RC construction produces between 17.8 and 40.1kg/m^2 of waste. On the other hand, the formwork cost is considered the major expenditure in a new in-situ RC construction project. Paul et al. [7] highlighted that this cost reaches more than 60% of the overall cost, of which the formwork materials cost 10% and the additional 50% is for the formwork labour. Moreover, the formwork preparation time is another problem in in-situ RC construction, as it consumes between 50% to 70% of the total construction duration [8, 9, 10]. The time taken by the formwork setting causes an extra cost loss via the delay in the financial return and the investment start of the project. In terms of health and safety, concrete formwork structures are recorded to have the highest number of worker-related injuries in the construction sector, double the accidents registered by other industries [11]. This conclusion brings great attention to an additional construction cost because the injury compensation payment received by construction sector workers is about twice that of other industries [12]. Due to the drawbacks of concrete formwork structures, engineers are now being encouraged to use novel technology like 3D Concrete Printing (3DCP) to provide cheaper, faster, safer and more sustainable construction solutions.

3DCP is an automated additive manufacturing technique, which uses either a gantry or robotic arm printer [9] to print successive layers of concrete, one on top of the other. This technique allows limitless geometric configurations for the printed elements or walls, which provides architectural freedom. Much like a conventional printer, a nozzle attached to the gantry or the robotic arm acts as the printing mechanism, while the concrete plays the role of the ink. A specialised mix with several admixtures must be used to ensure that each layer hardens faster but remains viscous enough and does not set too fast to adhere adequately to the next layer. In order to achieve quality in printing, five tests were designed for the concrete mix employed in 3DCP: flowability, extrudability, buildability, open time and compressive strength [13, 14]. Although 3DCP technology is a relatively new technology, it is currently attracting a lot of attention because of its advantages of low waste generation, sustainability, construction duration, construction costs and worker safety. Regarding sustainability, 3DCP creates almost zero waste, requires less transportation during the construction process and hence has a lower carbon footprint [15, 16]. Furthermore, the fact that no formwork is used brings a substantial positive sustainability impact as it reduces the number of trees cut for timber formwork and minimises the post-construction waste from the used and unused formwork moulds. Moreover, as mentioned above, the absence of formwork causes a significant reduction in construction cost and duration. Besides the reduction in labour, 3DCP also offers an improvement in the health and safety of the workers during construction, especially in harsh environments [17].

Despite all the advantages of 3DCP, there are still some points of concern. For example, there is still a high level of unpredictability with the concrete mix and its constituents, which in turn increases the total project cost. The concrete material cost for 3DCP is about twice that of conventional construction [18]. Furthermore, the printers are also relatively expensive, depending on the size and the degrees of freedom provided. However, gantry printers tend to be slightly cheaper than robotic arm printers and are often used for printing complete structures rather than individual structural elements. Nevertheless, 3DCP is expected to revolutionise construction with future research focusing on this area. Currently, there is no reliable output to understand the true efficiency of 3DCP in construction, despite a few studies that compare 3DCP with other construction techniques [17,18,19,20]. Previous work has shown the efficiency of 3DCP in cost, construction duration and environmental impact, particularly when the printed element is complex and curved [18, 71]. However, the market is still looking for more reliable answers regarding 3DCP. Therefore, this paper aims to contrast multiple construction techniques with 3DCP in terms of costs, construction duration and sustainability. The comparison includes cast-in-situ RC construction, CFS, HRS and Prefabricated Modular Construction (PMC) for the erection of a 257-villa compound in the UAE.

2. Research contribution and methodology

Although the reputation of 3DCP in the construction market is growing, the growth is slow due to the lack of and discrepancy in reliable data. Most of the obtainable data related to 3DCP are from the market with no robust research. Previous research studies emphasised the advantages of 3DCP via small elements, such as a printed wall or small unit, while it is rare to find a comparison between 3DCP and other construction techniques for buildings. Therefore, this research makes a significant contribution to the field by answering some important questions regarding the efficiency of 3DCP in terms of cost, sustainability and construction duration of buildings.

In this research, a two-storey villa from a residential development in the UAE was designed using five construction techniques: 3DCP, PMC, in-situ RC, CFS and HRS. The material quantities were estimated for each construction type. An analysis was then performed to evaluate the weight of the building, the construction duration and cost, and the CO_2 emissions from the production of the materials used in each construction strategy. The data from the analysis was later synthesised and discussed to compare 3DCP with other construction types.

3. Project description

Gardenia Town-Homes is one of three large-scale residential developments in the Al-Wasl Gate project located in Jebal Ali, Dubai. This compound was developed by the DuBox company in 20 months. The project has a total built-up area of approximately 64,700m^2 and encompasses 257 two-storey villas of 3.3m storey-height. The entire modules, fitted with services, were assembled off-site and later installed in situ. Each villa comprises eight modules, therefore a total of 2024 boxes were required for the project. Figure 1 shows the configuration and dimensions of one modular precast villa, which will be redesigned using other construction materials. The total area of this villa is 219.3m^2 and it was estimated to have a variable live load of 1.5 kN/m^2 based on the BS EN 1991-1-1:2002 [21] and the UK national annex of NA to BS EN 1991-1-1:2002 [22] for A1 sub-category loaded area. To design the project's foundation, it was assumed that the soil bearing capacity is 100 kN/m^2, the same as is recorded and commonly available in the UAE.

Fig. 1. The modular precast villa of eight boxes designed by DuBox.

4. Material quantity

4.1. Prefabricated Modular Construction (PMC)

From Figure 1, it can be seen that each precast module is a composite of solid RC wall panels, a ribbed RC floor panel and a solid RC roof panel. The prefabricated villa was placed on a 100mm thick non-reinforced concrete layer. Table 1 shows the estimated quantities for each part of the modular villa. The total concrete quantity employed for one villa is $155m^3$, while the total weight of added steel reinforcement is 12,756 kg. This brings the overall reinforcement ratio to $82.2 kg/m^3$, which is close to the 85% estimation by Cobb [23] for typical RC buildings. According to Weng et al. [24], for a precast unit of $2.43m^2$ area, the steel reinforcement was taken as $120 kg/m^3$ for slab and $60 kg/m^3$ for walls. It can be seen that the reinforcement used in Table 1 for the current project is higher. This is because the unit studied by Weng et al. [24] is a one-storey unit with smaller dimensions than the two-storey villas in the current project.

Table 1. Estimated material quantities for the prefabricated modular RC villa.

Structural Element	**Concrete Volume** (m^3)	**Steel Reinforcement** (kg)	**Reinforcement Ratio** (kg/m^3)
Precast Floor Slab	19.51	2780	143
Precast Roof Slab	29.57	2366	80
Precast Exterior Walls	25.06	2381	95
Precast Interior Walls	54.4	3264	60
Extra Precast Elements	14.56	1966	135
Concrete layer below villa	11.5	0	0
Total	155	12756	-

4.2. 3D Concrete Printing (3DCP)

The precast villa in Figure 1 was redesigned using the 3DCP technique. It was intended to use 3DCP without steel reinforcement addition. Therefore, the only printed elements are the walls as they can efficiently act as bearing walls without the need for reinforcement. In contrast, precast hollow-core panels were selected for the slabs under bending to avoid using formwork. The walls were assumed to be printed on an in-situ strip foundation. An additional 100mm thick in-situ concrete layer was provided below the foundation. As no steel reinforcement was used in the printed walls along with the absence of a set coding standard for designing the 3DCP elements, the bearing capacity of the wall was taken as follows:

$$f_{b,3DCP} = \frac{0.6 f_{ck}}{\gamma_c} \quad (1)$$

where f_{ck} is the characteristic compressive strength of the concrete material before printing. In this project, f_{ck} was assumed to have a value of 40MPa. γ_c is a partial safety factor; in this work, the partial safety factor was taken as 1.5 because it is applicable for concrete [25] and unreinforced masonry structures [26].

Previous experimental research on 3DCP elements shows that the concrete ink material can have a compressive strength of more than 40MPa. It was also recorded that the reduction in the compressive strength for the printed samples is no more than 40% of the mould cast samples [27, 28, 29, 30]. Therefore, applying the 0.6 reduction factor in Equation (1) is safe.

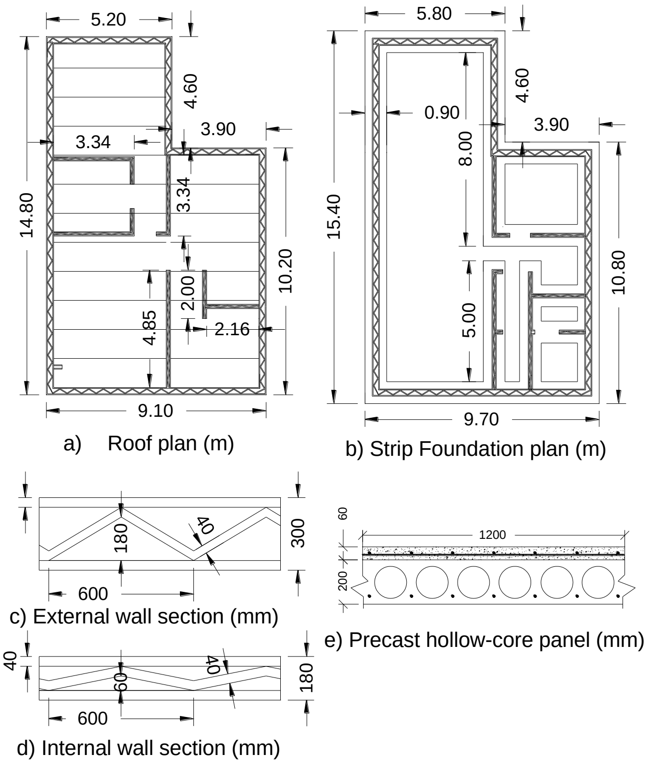
Figure 2 shows the roof plan with the precast panels, the strip foundation plan, sections in the printed external and internal walls, and the precast hollow core slab section. The configuration of the printed walls was selected according to industry practice in 3DCP [19, 20, 31]. The thickness of the printed walls was selected as 300mm and 180mm for the external and internal walls, respectively, even though that some references for implemented 3DCP buildings have chosen 400mm [15] and 500mm [31]. However, the thicker walls in the already-printed buildings are due to the embedded steel reinforcement to make frame elements. Hence, there is no need for a thick wall in the current project because the printed walls are unreinforced. As so, the current wall thickness satisfies Equation (1) safely. The thickness of the printed layers was assumed to be 40mm as ranges between 35mm to 45mm have been recorded elsewhere [31]. The printed wall configuration in Figure 2 leads to an ultimate axial compressive stress of 1.15 MPa under gravity loads, which is much smaller than the maximum permissible compressive strength of 16 MPa by Eq. (1).

Compared to UnReinforced Masonry (URM), the most ancient construction material, unreinforced 3D concrete printing material has a much greater loading capacity. This conclusion is derived from the fact that while the average uniaxial compression and tensile strength for URM are 5MPa and 0.95 MPa, respectively [73], 3DCP material recorded compressive strength of 29MPa and tensile strength of 2.35MPa at the lowest [30]. Moreover, an experimental test on a URM building of 229mm brick thickness by Shahzada et al. [74, 75] demonstrates that the ultimate capacity of their URM building reaches 31% of its total weight. On the other hand, the seismic design load by ASCE 7-10 [76] for the 3DCP building of the current project is 25% of its weight, which shows that 3DCP is, in fact, safer than URM. Hence, due to the high strength of 3DCP material, the absence of reinforcement does not affect the structural performance for low-rise structures and can be used for effective comparison against the reinforced concrete/ steel buildings.

Table 2 shows the quantities of the materials for the villa using 3DCP. It can be seen that the villa is a combination of unreinforced printed concrete and conventional concrete. A total volume of $54 m^3$ of printed concrete was used, whilst $33.4 m^3$ of conventional concrete was used for the precast hollow core slab with a post-tensioned bars ratio of 47%. Furthermore, $14.85 m^3$ of in-situ concrete was used for the foundation with a steel reinforcement ratio of 70%. The steel reinforcement percentage meets the typical reinforcement quantities for reinforced concrete footings [23]. For proper comparison with the PMC villa, plastering was added to the internal-printed walls and the interior face of the external-printed walls (Table 2).

Table 2. Estimated material quantities for the 3DCP villa.

Structural Element	**Reinforcement (kg)**	**Concrete Volume (m^3)**	**Plastering (m^2)**
External Printed Walls	-	36.91	307
Internal Printed Walls	-	16.67	278
Precast Hollow Core Slab	1575.32	33.40	-
Strip Foundation	1039.50	14.85	-
Concrete below foundations	-	7.19	-



a) Roof plan (m)

b) Strip Foundation plan (m)

c) External wall section (mm)

e) Precast hollow-core panel (mm)

d) Internal wall section (mm)

Fig. 2. The 3DCP villa: a) Roof plan with precast panels; b) Strip foundation plan; c) Printed external wall section; d) Printed internal wall section; e) Precast hollow-core slab section.

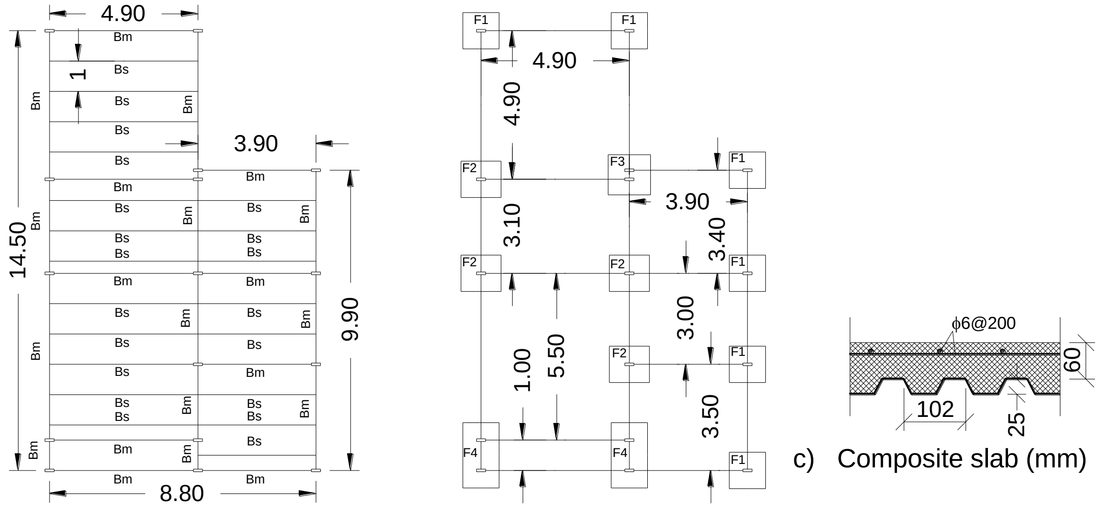
4.3. Cold Formed Steel (CFS)

The villa was designed using CFS material based on BS 5950-5:1998 [32]. The slab was assumed to be a composite concrete-steel corrugated deck supported by purlins with a 1m centre-to-centre spacing. The primary beams are supported by columns to isolated foundations (Figure 3). The RC foundations were designed using BS EN 1992-1-1: 2004 [25]. The external walls were assumed to be thermally insulated sandwich walls composed of normal weight blocks of 400mm x 250mm x 200mm from Hussain Mohd. Abbas Block Factory in the UAE market [33], while fire-resistant gypsum boards from Knauf Factory [34] and mineral wool insulation were presumed to be used for the internal walls. Additionally, plastering was also applied for the external walls along with a fire-rated false ceiling. This was done to ensure the CFS sections are protected against fire with the aim of approaching the fire resistance provided by concrete structures for proper and effective comparison. Table 3 summarises the outcomes of the villa design using CFS. It is worth mentioning that the CFS weight for the frame system was amplified by a factor of 1.3 to consider the weight of steel connections. The quantity of CFS for the frame system of this villa reaches 38kg/m^2, which meets ArcelorMittal [35]'s range of 35 to 50 kg/m^2 for low-rise (two to six stories) steel buildings. Additionally, Table 3 shows that the steel reinforcement percentage in the foundation was assumed to be 70% to confirm the estimated reinforcement value for isolated footings from the reinforced concrete practice [36].

Table 3. Estimated material quantities for the CFS villa.

Structural Element	**Dimensions (mm)**	**CFS weight** (kg)	**Reinforcement** (kg)	**Concrete Volume** (m^3)	**Plastering** (m^2)	**Fire-rated false ceiling** (m^2)
Corrugated Steel Deck	-	1655.9	482.1	16.0	-	219.3
Columns (Ground level)	2 C (302 × 89 × 2.3)	1210.1	-	-	-	-
Columns (First-floor level)	2 C (172 × 69 × 1.4)	478.4	-	-	-	-
Primary Beams (Bm)	2 C (342 × 97 × 2.5)	4405.8	-	-	-	-
Secondary Beams (Bs)	1 C (302 × 89 × 2.5)	2237.0	-	-	-	-

Isolated Foundation (F1)	1200 × 1200 × 250	-	151.2	2.2	-	-
Isolated Foundation (F2)	1350 × 1200 × 250	-	113.4	1.6	-	-
Combined Foundation (F3)	1400 × 1350 × 250	-	33.1	0.5	-	-
Combined Foundation (F4)	2150 × 1200 × 250	-	90.3	1.3	-	-
Concrete below foundations	-	-	-	2.6	-	-
Tie beams between foundations	250x250	-	236.3	3.4	-	-
External walls	280×10^6 mm^2	-	-	-	560.0	-
Internal walls	126×10^6 mm^2	-	-	-	-	-



c) Composite slab (mm)

a) Roof plan (m) b) Isolated foundations plan (m)

Fig. 3. The CFS and HRS villa: a) Roof plan; b) Foundation plan; c) Steel-concrete composite slab.

4.4. *Hot Rolled Steel (HRS)*

The same structural plans shown in Figure 3 were redesigned using HRS material and Eurocode 3 standard [37]. The only difference from the CFS villa is the type of steel sections shown in Table 4. The steel weight of the HRS frame (Table 4) is 48kg/m^2, which is 26% higher than the value obtained from the CFS design under the same load system. Nevertheless, it is still within the aforementioned range of steelwork practice [35]. It is worth noting that the designed values were multiplied by an assumed factor of 1.3 to consider the additional steel required for member connections.

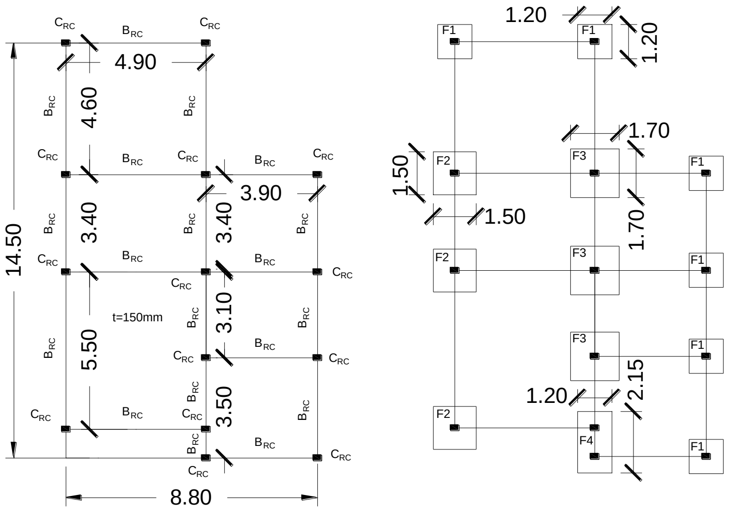
Table 4. Estimated material quantities for the HRS villa.

Structural Element	**Dimensions (mm)**	**CFS weight** (kg)	**Reinforcement** (kg)	**Concrete Volume** (m^3)	**Plastering** (m^2)	**Fire-rated false ceiling** (m^2)
Corrugated Steel Deck	-	1655.9	482.1	16.0	-	219.3
Columns (Ground level)	UKB 178x102x19	1304.2	-	-	-	-
Columns (First-floor level)	UKB 152x89x16	1098.2	-	-	-	-
Primary Beams (Bm)	UKB 254x102x25	5135.0	-	-	-	-
Secondary Beams (Bs)	UKB 127x76x13	3042.0	-	-	-	-
Isolated Foundation (F1)	1200 × 1200 × 250	-	151.2	2.2	-	-

Isolated Foundation (F2)	1350 × 1200 × 250	-	113.4	1.6	-	-
Combined Foundation (F3)	1400 × 1350 × 250	-	33.1	0.5	-	-
Combined Foundation (F4)	2150 × 1200 × 250	-	90.3	1.3	-	-
Concrete below foundations	-	-	-	2.6	-	-
Tie beams between foundations	250x250	-	236.3	3.4	-	-
External walls	280x10^6 mm^2	-	-	-	560.0	-
Internal walls	126x10^6 mm^2	-	-	-	-	-

4.5. Reinforced Concrete (RC)

The design of the villa was repeated using RC material. The concrete's characteristic compressive strength was assumed as 40MPa and the yield strength of the steel reinforcement was 500MPa. The slab was designed as a 150mm thick solid slab. External and internal walls for the RC villa were assumed to be of the same specifications as those used in the CFS and HRS villas. Table 5 summarises the results of the RC design using BS EN 1992-1-1: 2004 [25]. Figure 4 demonstrates the floor and foundation plans.



a) Roof plan (m) b) Isolated foundations plan (m)

Fig. 4. The RC villa: a) Roof plan; b) Foundation plan.

Table 5. Estimated material quantities for the RC villa.

Structural Element	**Dimensions (mm)**	**Reinforcement** (kg)	**Concrete Volume** (m^3)	**Reinforcement Ratio** (kg/m^3)	**Plastering** (m^2)
RC solid slab	150.0	2631.8	32.9	80.0	-
RC Columns (C$_{RC}$)	200x300	776.2	5.5	140.0	-
RC Beams (B$_{RC}$)	200x450	1566.0	13.1	120.0	-
Isolated Foundation (F1)	1200 × 1200 × 250	151.2	2.2	70.0	-
Isolated Foundation (F2)	1500 × 1500 × 350	165.4	2.4	70.0	-
Combined Foundation (F3)	1700 × 1700 × 400	242.8	3.5	70.0	-
Combined Foundation (F4)	2150 × 1200 × 250	45.2	0.6	70.0	-
Concrete below foundations	-	-	3.0	-	-
Tie beams between foundations	200x400	392.0	5.6	70.0	-

External walls	280x10^6 mm^2	-	-	560.0
Internal walls	126x10^6 mm^2	-	-	-

Table 5 shows the reinforcement ratios assumed for each structural element from practical experience [23, 36]. This brings the overall reinforcement ratio to 87%, which almost matches Cobb's estimation [23]. On the other hand, Table 5 shows that the quantities of materials per square metre of floor area are 0.31 m^3/m^2 and 27.2 kg/m^2 for concrete and steel reinforcement, respectively. Thiruvengadam et al. [38] estimated that a two-storey RC building in a low seismic zone, such as the UAE requires 0.26 m^3/m^2 of concrete and 29 kg/m^2 of steel reinforcement, which in turn validates the design conclusions of the current study.

5. Design outcomes analysis

From the design outcomes, the total material quantities were calculated for each type of construction method and summarised in Table 6. The material quantities were converted to represent the quantities per square metre of the total area (219.3m^2) of the villa. It can be observed from Table 6 that the PMC construction method utilises the greatest quantity of concrete, followed by the 3DCP technique. This is because the walls and slabs in PMC are made entirely of precast reinforced concrete panels and similarly, the internal and external walls in 3DCP are printed solely with concrete. In contrast, the other construction techniques used non-concrete walls, which in turn explains the significantly lower concrete utilisation ratio per unit area.

Table 6. Total material quantities for each construction method.

Type of Material	**Total Material Quantities**				
	PMC	**3DCP**	**CFS**	**HRS**	**RC**
Roof corrugated steel sheet (kg/m^2)	-	-	7.55		
CFS work (kg/m^2)	-	-	38.00	7.55	-
HRS work (kg/m^2)	-	-	-	48.24	-
Precast and In-situ Concrete work (m^3/m^2)	0.70	0.25	0.13	0.13	0.31
3D printed Concrete work (m^3/m^2)	-	0.24	-	-	-
External thermal insulated block wall (m^2/m^2)	-	-	1.27	1.27	1.27
Internal Fire-resistant gypsum board wall (m^2/m^2)	-	-	0.58	0.58	0.58
Plastering (m^2/m^2)	-	2.67	2.55	2.55	2.55
Fire-rated false ceiling (m^2/m^2)	-	-	1.00	1.00	-

5.1. Structure weight

From the material quantities in Table 6, the weight for each type of villa was derived, as seen in Table 7. The unit weight shown in Table 7 for each item was assumed using the typical unit weight for building materials. For steelwork items, no change in the weight values of Table 6 was applied since they are already in units of kg/m^2. However, the steel members' weight was found based on a density of 7850 kg/m^3 [21]. The RC concrete and unreinforced concrete densities were assumed to be 2500 kg/m^3 and 2300 kg/m^3, respectively [21]. The unit weight of the thermally insulated block walls and fire-resistant gypsum board walls were taken from the supplier's datasheet [33, 34]. The plastering density was considered as 2000 kg/m^3 [21] for cement mortar material 20mm thick for one wall face. Therefore, the unit weight for plastering was 40 kg/m^2, as seen in Table 7. The fire-rated false ceiling unit weight was assessed using Eq. (2):

$$\text{Ceiling unit weight} = \text{Ceiling tile weight} + \text{Service load} + \text{Grid weight} \tag{2}$$

The ceiling weight was taken from the Knauf Factory datasheet [34] for the fire-resistant gypsum board (10.4 kg/m^2). Additionally, a minimum service load of 3 kg/m^2 was assumed and a grid weight of 1 kg/m^2 was estimated [39].

By mapping the unit weight in Table 7 onto the material quantities in Table 6, the weight per square metre was evaluated corresponding to the construction material and technique.

Table 7. Weight per square metre for each villa type.

	Type of Material	Unit Weight	Weight (kg/m^2)				
			PMC	3DCP	CFS	HRS	RC
Structural activity	**Roof corrugated steel sheet**	1 kg/kg	-	-	7.6	7.6	-
	CFS work	1 kg/kg	-	-	38.0	-	-
	HRS work	1 kg/kg	-	-	-	48.2	-
	Precast and In-situ Concrete work	2500 kg/m^3	1762.3	631.9	313.5	313.5	783.9
	3D printed Concrete work	2300 kg/m^3	-	562	-	-	-
Non-Structural activity	**External thermal insulated block wall**	288 kg/m^2	-	-	367.2	367.2	367.2
	Internal Fire-resistant gypsum board wall	21 kg/m^2	-	-	12.1	12.1	12.1
	Plastering	40 kg/m^2	-	106.8	102.0	102.0	102.0
	Fire-rated false ceiling	14.4 kg/m^2	-	-	14.4	14.4	-
Structure (structural activity) weight kg/m^2			1762	1194	359	369	784
Total weight kg/m^2			1762	1301	855	865	1265

5.2. Construction duration

It is vital that construction techniques are developed so that they are not only cost-effective but also more time-efficient. As the return of investment is another important factor in construction, faster construction techniques also reduce project costs and enhance the associated cost-benefit.

Table 8 shows the work activities assumed in this research. The non-structural activities were added to make the in-situ construction techniques comparable with the off-site PMC method since the PMC unit is fitted with plastered walls from the manufacturer. For each work activity, the number of workers and the duration of eight-hour workdays were estimated per unit based on the UAE construction practice. By mapping workers' number and the 8-hour days per unit for each described activity in Table 8 onto the material quantities from Tables 1 to 5, the total man-hours per square metre were evaluated for each activity, then for each construction technique. Table 8 shows that PMC consumes the shortest construction period of 2.7 man-hours/m^2. Boafo et al. [40] reported that a 25-storey student residence of 824 modules in Wolverhampton, UK, was executed in 32 weeks at approximately 8.2 man-hours/m^2. However, it must be noted that the project in the current study is only a two-storey villa that requires much fewer logistics and man-hours than a 25-storey building because it was fully assembled off-site. In the current project, the on-site work is only carried out for the blinding concrete below the PMC modules. On the other hand, Table 8 does not consider the full finishing duration of the project; Weng et al. [24] estimated the finishing duration to be about 48% of the complete construction process for a precast unit.

According to Table 8, the 3DCP villa takes 9.8 man-hours/m^2. Aside from the non-structural activities, which demand 65% of the construction duration, the structure takes 3.5 man-hours/m^2. In other words, the current 219.3m^2 villa structure would be constructed in about 32 days using 3DCP, assuming three employees worked eight hours a day. It was reported that the Chinese Huashang Tengda company implemented a 400 m^2 two-storey 3DCP villa in 45 days [41]. The largest two-storey 3DCP building (640 m^2 total area) was completed in Dubai by the Apis Cor Company. It took 500 hours of machine time, working eight hours per day for 63 days [42]. In Russia in 2016, the same company printed a one-storey 38m^2 house in 24 hours (three days) [41]. Figure 5 shows the previous data for the printed two-storey buildings and also shows that the data passes a trendline as summarised in Equation 3:

$$\text{Execution time in days} = 0.074 \text{ x } (\text{Total area in m}^2) + 15.7 \tag{3}$$

Figure 5 confirms that the current research is at the same trend as previously printed projects in terms of print duration.

Structurally, Table 8 shows that CFS construction is much faster than the construction of the RC villa, with a 2.24-fold difference. Qureshi et al. [43] concluded that for the construction of a one-storey building without finishes, CFS is four times faster in construction than RC. Doctolero and Batikha [44] found that for a four-storey office building without finishes, RC construction is 2.64 times more time-consuming than CFS. However, the non-structural activities take a long time, as seen from Table 8. For CFS, the block-unit walls and plastering implementation covers about 50% of the total construction period.

Table 8. Man-hours per square metre for each type of villa.

Activity Description (unit)	Workers/unit	8-hour days/unit	Man-hours/m^2

				PMC	3DCP	CFS	HRS	RC
Structural activity	RC isolated Footing (m^3)	0.60	0.50	-	-	1.58	1.58	3.28
	RC strip Footing (m^3)	0.33	0.50	-	2.71	-	-	-
	Steel Framing (ton)	1.00	1.23	-	-	1.84	2.97	-
	RC in-situ columns (m^3)	2.00	0.35	-	-	-	-	0.78
	RC in-situ beams (m^3)	0.85	0.30	-	-	-	-	1.57
	RC in-situ slab (m^3)	0.45	0.15	-	-	-	-	2.68
	Steel-concrete composite Deck (m^2)	0.036	0.0045	-	-	0.28	0.28	-
	Hollow Core Slabs (m^2)	0.018	0.0045	-	0.14	-	-	-
	PMC off-site Work (m^3)	0.10	0.0210	1.57	-	-	-	-
	On-Site Concrete for PMC construction (m^3)	0.52	0.26	0.65	-	-	-	-
	Module installation (module)	8.00	1.5	0.44	-	-	-	-
	3DCP walls (m^3)	0.037	0.28	-	0.63	-	-	-
Non-Structural activity	External thermal insulated block wall (m^2)	0.017	0.10	-	-	4.86	4.86	4.86
	Internal Fire-resistant gypsum board wall (m^2)	0.063	0.055	-	-	2.01	2.01	2.01
	Plastering (m^2)	0.0054	0.066	-	4.45	4.06	4.06	4.06
	Cutting for services (m^2)	0.027	0.032	-	1.92	1.56	1.56	1.56
	Fire-rated false ceiling (m^2)	0.005	0.052	-	-	1.52	1.52	-
Man hours/m^2 (Structural activity)				2.7	3.5	3.7	4.8	8.3
Man hours/m^2 (Non-Structural activity)				-	6.4	14.0	14.0	12.5
Total man hours/m^2				2.7	9.8	17.7	18.8	20.8

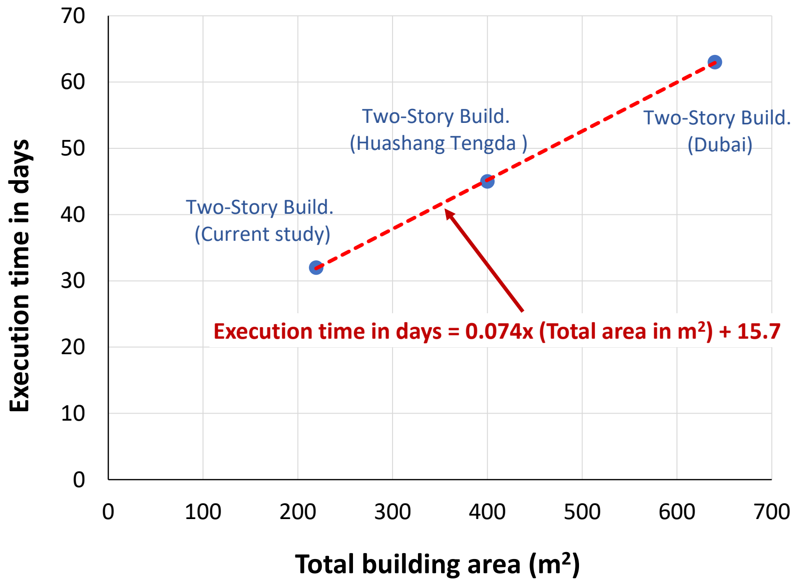


Fig. 5. Relationship between the total area of the building and the execution time for two-storey 3DCP buildings.

5.3. *Cost analysis*

The cost of a project can be divided into two categories: direct cost and indirect cost. The direct cost varies with the time required to complete the project and considers the cost of materials, labour, equipment, etc. In contrast, the indirect cost is a fixed cost that is independent of time (e.g., administrative fees, taxes). An overhead and profit are typically added for the service provided by the contractor. In the current research, the cost of the two-storey villa in concern was estimated using the unit rates of similar projects in the UAE.

5.3.1. Material cost

Table 9 shows the cost in terms of materials used in the building and each material's unit rate in AED. The final material cost was then calculated per square metre of the total building area (219.3m^2). Table 9 shows that the RC building has the least expensive material cost, while HRS is the costliest, followed by 3DCP. The cost of concrete material for 3DCP is 950 AED/m^3 (259 USD/m^3) and is about 3.8 times higher than the normal concrete cost of 250 AED/m^3 (68 USD/m^3). The 950 AED/m^3 (259 USD/m^3) was derived as an average of values available from various literature, such as the COBOD [45] estimation of about 986 AED/m^3 (269 USD/m^3) and the Holt et al. [17] estimation of 918 AED/m^3 (250 USD/m^3)

Weng et al. [24] estimated the cost of 3DCP materials to be 123 USD/m^2 (453 AED/m^2). In the same research, the precast approach's material cost was assumed to be 118 USD/m^2 (434 AED/m^2). Note that Weng et al.'s work [24] is for a unit of 2.43m^2 floor area. Chan and Aibinu [46] also performed a study to compare the structural system cost using both cast-in-situ and precast construction in various locations. The research was conducted on a two-storey structure of 2405 m^2. It was shown that the cost of the concrete and steel reinforcement for the cast-in-situ technique accounts for 51 USD/m^2 (187 AED/m^2) in the USA, while it is 95 MYR/m^2 (86 AED/m^2, 23 USD/m^2) in Malaysia. From Table 9, the cost rate of the concrete and steel reinforcement materials used for the RC structure in the UAE is 145 AED/m^2 (40 USD/m^2). Chan and Aibinu [46] then found that the cost of material for the precast method is 336 MYR/m^2 (300 AED/m^2, 82 USD/m^2) in Malaysia, whereas the material costs for PMC in the UAE are 338 AED/m^2 (92 USD/m^2) (Table 9).

Table 9 shows that the CFS material cost is 30% higher than that of the RC and 23% lower than that of the HRS.

Table 9. Material cost per square metre for each type of villa.

Type of material (unit)	**Material cost AED/unit (USD/unit)**	**Total Material Quantities (unit/square building area)**				
		PMC	**3DCP**	**CFS**	**HRS**	**RC**
Roof corrugated steel sheet (ton)	1800 (490)	-	-	0.0076	0.0076	-
CFS (ton)	4100 (1117)	-	-	0.0380	-	-
HRS (ton)	5600 (1526)	-	-	-	0.048	-
Concrete (m^3)	250 (68)	0.052	0.101	0.125	0.125	0.314
Concrete for precast (m^3)	280 (76)	0.652	-	-	-	-
Reinforcement (ton)	2450 (667)	0.058	0.005	0.005	0.005	0.027
Concrete for 3DCP (m^3)	950 (259)	-	0.244	-	-	-
Hollow Core Slab (m^2)	151 (41)	-	1.000	-	-	-
External thermal insulated block wall (m^2)	95 (26)	-	-	1.275	1.275	1.275
Internal Fire-resistant gypsum board wall (m^2)	34 (9)	-	-	0.576	0.576	0.576
Plastering (m^3)	200 (54)	-	0.053	0.051	0.051	0.051
Fire-rated false ceiling (m^2)	20 (5.4)	-	-	1	1	-
Total Material cost (AED (USD)/square building area)		338(92)	430(117)	384(107)	498(136)	296(81)

Note: AED is the currency abbreviation for the United Arab Emirates' Dirham. To convert AEDs to USDs, a conversion factor of 0.272 can be used.

5.3.2. Total cost

Table 10 presents the total cost for each type of construction. The final cost was displayed per square metre of the total building area (219.3m^2). The cost of printed concrete was considered to be 2500 AED/m^3 (681 USD/m^3) using a gantry girder printer. This was deemed as a reasonable average of the costs available from multiple sources of literature. For example, the Office of the Future's printing in Dubai in 2016 cost USD 140,000 [47] for about 132m^3 printed concrete [31]. In other words, it costs 1060 USD/m^3 (3890 AED/m^3). Holt et al. [17] estimated the construction cost of a 150m^3 printed wall to be USD 40,500 (991 AED/m^3, 270 USD/m^3) to only supply and pump the concrete; printer and labour costs were not included. In a study by Nerella et al. [48], the machine and labour costs were taken as 210 Euro/h (916 AED/h, 250 USD/h), which is equivalent to 654 AED/m^3 (178 USD/m^3) if the concrete is to be extruded at a rate of 1.4

m^3/h [45]. Besides, Nerella et al. [48] considered that the material costs are 130 Euro/m^3 (567 AED/m^3, 154 USD/m^3). Therefore, according to Nerella et al. [48], the total printing cost is 1221 AED/m^3 (333 USD/m^3), where it can be seen that the machine and labour costs are valued at 115% of the material cost and 54% of the total printing cost. If this conclusion is implemented into the study by Holt et al. [17], the final printing cost can be predicted as 2131 AED/m^3 (581 USD/m^3).

From these conclusions, the current estimation of 2500 AED/m^3 (681 USD/m^3) for printing costs is appropriate as it covers the discrepancies in printing costs seen in the literature for using a gantry girder printer. It is worth noting that using a robotic arm printer is much more costly than a gantry girder printer. García de Soto et al. [18] estimated that the total printing cost (labour + material + equipment) is 1418 USD/m^3 (5202 AED/m^3) for a straight concrete wall of 4.39m^3 print volume using a robotic arm printer. For a double-curved wall, the cost of the printing process using a robotic arm printer was found to be 1528 USD/m^3 (5610 AED/m^3).

5.3.3. Construction cost

From Table 9 (for the material cost) and Table 10 (for the total cost), the construction cost can be extracted for each construction technique. Figure 6 shows the relative percentage of the construction cost of the total cost, which accounts for 55% of the total cost in 3DCP (Figure 6). The construction cost was found to be 62% of the total cost by Nerella et al. [48], while Weng et al. [24] estimated the construction cost for 3DCP to cover 70% of the total cost. It should be noted that a robotic arm was used for 3DCP in the study by Weng et al. [24], which explains the high construction cost compared to the current study that focuses on a gantry girder printer. García de Soto et al. [18] proposed a similar finding of 72% for a robotic arm 3DCP. Alternatively, Zhang et al. [9] stated that the material consumes about half of the total cost in the 3DCP method, with about 35% for labour and 20% for equipment.

Lawson and Ogden [49] reported that the material cost accounts for 20% of the total cost in modular construction, whereas it is 30% in conventional construction. Paul et al. [7] addressed a 30% material cost in conventional concrete work.

Figure 6 also shows that the material cost for CFS shares 41% of the total cost, whereas it is 47% in the case of HRS.

Table 10. Total cost per square metre for each villa type.

Type of construction work (unit)	**Total cost AED/unit (USD/unit)**	**Total Material Quantities (unit/square building area)**				
		PMC	**3DCP**	**CFS**	**HRS**	**RC**
Roof corrugated steel sheet (ton)	3000 (817)	-	-	0.0076	0.0076	-
CFS (ton)	5200 (1417)	-	-	0.038	-	-
HRS (ton)	6500 (1771)	-	-	-	0.048	-
RC slab work (m^3)	1400 (381)	-	-	-	-	0.150
RC columns work (m^3)	1800 (490)	-	-	-	-	0.025
RC beams work (m^3)	1600 (436)	-	-	-	-	0.060
RC footings work (m^3)	1000 (272)	0.052	0.101	0.052	0.052	0.079
RC for the composite roof (m^3)	1400 (381)	-	-	0.073	0.073	-
RC modular precast (m^3)	1500 (409)	0.652	-	-	-	-
Assembly and production (m^2)	200 (54)	1	-	-	-	-
Transportation to site (m^2)	80 (22)	1	-	-	-	-
Site Cranes working (m^2)	50 (14)	1	-	-	-	-
Printed Concrete (m^3)	2500 (681)	-	0.244	-	-	-
Hollow Core Slab (m^2)	166 (45)	-	1.000	-	-	-
External thermal insulated block wall (m^2)	180 (49)	-	-	1.275	1.275	1.275
Internal Fire-resistant gypsum board wall (m^2)	150 (41)	-	-	0.576	0.576	0.576
Plastering (m^2)	22 (6)	-	2.669	2.550	2.550	2.550
Fire-rated false ceiling (m^2)	180 (49)	-	-	1	1	-
Cutting for service (m^2)	10 (2.72)	-	1.851	1.851	1.851	1.851
Total cost (AED (USD)/square building area)		1361(371)	954(260)	945(257)	1061(289)	820(223)

Note: AED is the currency abbreviation for the United Arab Emirates' Dirham. To convert AEDs to USDs, a conversion factor of 0.272 can be used.

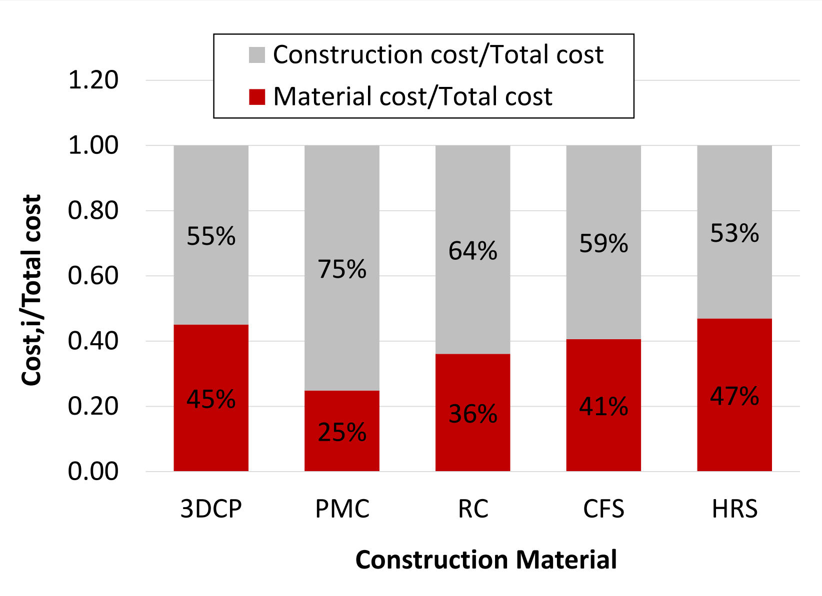


Fig. 6. The relative percentage of material cost and construction activity of total cost.

5.4. CO_2 emissions from material production

To estimate the total CO_2 emissions for each construction type, the CO_2 emissions for each component were evaluated using the existing literature review (Table 11). The final CO_2 emissions for concrete in Table 11 were taken as the mean of the values available for conventional and recycled concrete. Table 11 also shows that the production of CFS sections has much lower CO_2 emissions than HRS as CFS is recycled from steel scraps, avoiding primary steel production [56]. Therefore, CFS production results in 1.15 kg CO_2/kg less than HRS (Table 11). The CO_2 emissions for 3D printed concrete depend on the concrete mix ingredients that confirm the concrete's rheological and hardened properties for printing. Table 11 presents many trials for printed concrete mixtures. The CO_2 emissions were calculated using the CO_2 emissions for each material component [51]. It can be seen that CO_2 emissions for 3DCP mixtures range between 317 kg CO_2/m^3 and 631 kg CO_2/m^3 (Table 11). This range almost matches the review by Bhattacherjee et al. [72], where the CO_2 emissions for OPC-printable concrete mixes are in the domain of 330 kg CO_2/m^3 and 680 kg CO_2/m^3. The final CO_2 emission figure is the mean of the values presented in Table 11.

Table 11. CO_2 emissions for each material used in this research

Material type	**Description**	**CO_2 emissions**	**References**	**Final/ Average**
Concrete	Conventional concrete	343 kg CO_2/m^3	[50, 51]	286 kg CO_2/m^3
	Recycled concrete (20% Ceramic Waste Powder, 100% Recycled Coarse Aggregate, 20% Ceramic Fine Aggregate)	267 kg CO_2/m^3	[51]	
	Recycled concrete (50% GGBS, 100% Recycled Coarse Aggregate, 10% Silica Fume)	249 kg CO_2/m^3	[52]	
Steel reinforcement and HRS	-	1.83 kg CO_2/kg	[53, 54, 55]	1.83 kg CO_2/kg
CFS	Steel production from 100% Scrap using Electric Arc Furnace (EAF)	0.4 kg CO_2/kg	[53, 56, 57]	0.68 kg CO_2/kg
	Pickling	0.04 kg CO_2/kg	[57]	
	Cold rolling	0.05 kg CO_2/kg	[57]	
	Galvanising	0.09 kg CO_2/kg	[57]	

	Slitting	0.01 kg CO_2/kg	[57]	
	Blanking	0.02 kg CO_2/kg	[55, 57]	
	Stamping	0.07 kg CO_2/kg	[55, 57]	
Concrete for 3DCP	Cement (864 kg/m^3), Silica Fume (36 kg/m^3), Fine Aggregate (900 kg/m^3), water (315 L/m^3), 0.3% admixture	631 kg CO_2/m^3	[58]	440 kg CO_2/m^3
	Cement (540 kg/m^3), Silica Fume (60 kg/m^3), Fine Aggregate (1357 kg/m^3), water (259 L/m^3), 0.16 % admixture	404 kg CO_2/m^3	[14]	
	Cement (430 kg/m^3), Fly Ash (170 kg/m^3), Fine Aggregate (1420 kg/m^3), water (180 L/m^3), Superplasticizer (10 L/m^3)	345 kg CO_2/m^3	[48]	
	Cement (579 kg/m^3), Fly Ash (165 kg/m^3), Silica Fume (83 kg/m^3), Fine Aggregate (1167 kg/m^3), water (261 L/m^3), 1.48 % Superplasticizer	452 kg CO_2/m^3	[59]	
	Cement (391 kg/m^3), Fly Ash (213 kg/m^3), Silica Fume (213 kg/m^3), Fine Aggregate (1260 kg/m^3), water (138 L/m^3), Superplasticizer (11 L/m^3)	317 kg CO_2/m^3	[48]	
	Cement (663 kg/m^3), Fly Ash (166 kg/m^3), Fine Aggregate (1243 kg/m^3), water (265 L/m^3), 0.1% Superplasticizer	490 kg CO_2/m^3	[60]	
Internal wall	2 gypsum board with steel stud	26 kg CO_2/m^2	[61]	30 kg CO_2/m^2
	Rockwool	0.74 kg CO_2/kg	[62]	
Brick external wall	-	78 kg CO_2/m^2	Building energy data book 2011, 2012	78 kg CO_2/m^2
Cement Plaster	Cement (400 kg/m^3), Fine Aggregate (1200 kg/m^3), water (280 L/m^3)	300 kg CO_2/m^3	-	300 kg CO_2/m^3

By mapping Table 11 onto the material quantities, the CO_2 emissions for each type of construction were evaluated, as seen in Table 12. It can be observed from Table 12 that the CO_2 emissions of the PMC structure are the same as the total CO_2 emissions because there are no non-structural activities applicable in the PMC technique.

Table 12. CO_2 emissions for each type of construction.

Material type		**Material quantities for each construction type**				
		3DCP	**PMC**	**RC**	**CFS**	**HRS**
Structural activity	Cold Formed Steel (kg/m^2)	0	0	0	45.542	7.551
	Hot Rolled Steel (kg/m^2)	0	0	0	0	48.242
	Concrete (m^3/m^2)	0.253	0.705	0.314	0.125	0.125
	Steel Reinforcement (kg/m^2)	11.923	58.167	27.225	5.045	5.045
	Printed concrete (m^3/m^2)	0.244	0	0	0	0
Non-structural activity	External walls (m^2/m^2)	0	0	1.275	1.275	1.275
	Internal walls (m^2/m^2)	0	0	0.576	0.576	0.576
	Cement Plaster (m^3/m^2)	0.053	0	0.051	0.051	0.051
	Fire-rated false ceiling (m^2/m^2)	0	0	0	1	1
	CO_2 emissions, structure/structural activity (kg CO_2/m^2)	202	308	140	76	139
	CO_2 emissions, total (kg CO_2/m^2)	218	308	272	221	284

6. Discussion

Figure 7 presents the findings of Tables 7, 8, 10 and 12 by comparing each construction technique relative to 3DCP in terms of the total weight of the structure, total man-hours, total cost and total CO_2 emissions.

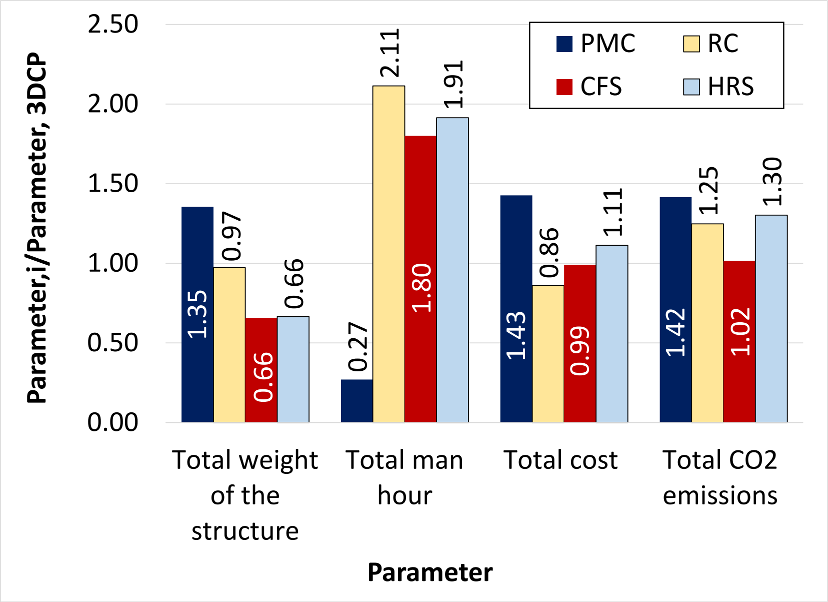


Fig. 7. The relative factor between a construction method and 3DCP technique.

6.1. Influence of construction method on the weight of the structure

From Figure 7, it can be seen that steel structures are the lightest of the construction materials, while PMC is the heaviest and has 35% more mass than 3DCP. The RC structure is almost the same as the 3DCP structure in terms of weight and is found to be only 3% lighter. This has to be acknowledged in the seismic active zone, where weight inversely affects structural integrity.

By constructing a bathroom unit using two techniques, precast concrete and 3DCP, Weng et al. [24] estimated the unit weight and showed that the precast unit is heavier than the 3DCP unit by 36%; almost the same as the current study.

Doctolero and Batikha [44] proved that in comparison to RC sections, CFS sections can reduce the weight of the structure by 40%. Similarly, CFS was found to be 32% lighter than RC in the current study. Doctolero and Batikha [44] studied a four-storey building and did not cover the finishing of the building, whereas the completion of brick walls, which impacts the weight of the CFS building considerably, is applied in the present research (Table 7). In terms of CFS and HRS, there is no significant difference in the weight, much like the findings of Doctolero and Batikha [44].

6.2. Influence of construction method on construction duration

Figure 7 displays that PMC is the most efficient in terms of man-hours, with a 270% reduction in comparison to 3DCP. On the other hand, the in-situ RC method is the most time-consuming and requires the greatest amount of man-hours, 111% greater than 3DCP. Although CFS takes around 1.8 times the man-hours required for 3DCP, the non-structural activities (e.g., externally insulated walls, plastering) consume much more time and make the construction solution relatively time-consuming.

Philip and Kannan [63] concluded that a considerable amount of time is saved when using PMC in comparison to precast and cast-in-situ techniques. It was reported that PMC takes 155% and 44% less time than RC and precast, respectively.

Data comparing 3DCP to other construction methods are very limited and available only by the market. Based on the market statement, Hossain et al. [64] claimed that 3DCP reduces construction time by 50-70% over conventional construction. However, Weng et al. [24] showed that precast construction is 27% longer than 3DCP. Gaudillière et al. [20] showed that for the construction of a rain collector in Lille of dimensions 2.15m x 2.2m x 2.6m, 3DCP reduced the time by 23% in comparison to the cast-in-situ RC technique. The discrepancy in the literature about the construction time of 3DCP compared to other construction methods is clear. This is due to factors like the geometric configurations and the area of the constructed unit, and the effect of non-structural activities, which highly impact construction time (Table 8).

Steel structures recorded shorter construction times, ranging from 9% to 15% less than RC construction (Figure 7). ArcelorMittal [65] indicated that the range is from 5% to 15% depending on the used prefabrication.

6.3. Influence of construction method on total construction cost

Figure 7 demonstrates that PMC construction is 43% more costly than 3DCP, while RC construction is 14% cheaper than 3DCP. The CFS construction cost is almost the same as 3DCP, whereas HRS is 11% more expensive. The high cost of the concrete mixture for printing plays an important role in raising the cost of 3DCP compared to the conventional concrete material used for RC construction (Table 9). However, it is also important to consider the influence of the construction period on the total cost of a project. A shorter construction duration saves direct expenditures associated with the project (e.g., labour cost) and allows an early return on investment. For example, Table 13 shows how the construction time affects the final construction cost through saving in the labour cost only. In Table 13, the labour cost in the UAE was estimated as 5.9 USD/hr (22 AED/hr), obtained from the AECOM [66] estimation. The reduction or addition in cost concerning construction duration was found by multiplying the labour cost rate by the variation in construction time from the 3DCP process. For instance, PMC consumes 7.1 hr/m^2 less than 3DCP, therefore, the saving is 156 AED/m^2 (43 USD/m^2) if the labour cost rate is assumed as 22 AED/hr (6 USD/hr). This reduces the final cost of PMC to 1205 AED/m^2 (328 USD/m^2) from 1361 AED/m^2 (371 USD/m^2) compared to 954 AED/m^2 (260 USD/m^2) for 3DCP. In other words, 3DCP is more economical than PMC by 21%, if including the construction saving time of PMC. The same calculations were carried out for other construction techniques; in conclusion, 3DCP is 10%, 15% and 24% more economical than RC, CFS and HRS, respectively.

Weng et al. [24] concluded that using 3DCP in a bathroom unit construction reduces the cost by 25% in comparison to the precast method. Chan and Aibinu [46] estimated that cast-in-situ RC is 163% cheaper than the precast method in Malaysia, while it is only 10% cheaper in Australia. This highlights the effect of construction location on total project cost. Philip and Kannan [63] evaluated that PMC is 167% and 70% higher in cost than RC and precast concrete, respectively. In the current study, PMC is 66% more costly than RC without counting the advantage of the short construction duration of PMC. If the savings in labour cost are considered, then the PMC cost drops to 13% less than RC (Table 13).

Abu-Hamd and Abouhamad [67], counting the finishes, valued the total construction cost of an RC building as 2% and 17% less than using CFS and HRS, respectively. In the current study, RC construction is 15% cheaper than CFS and 29% cheaper than HRS. These percentages drop to 5% for CFS and 18% for HRS when considering construction duration (Table 13). It must be noted that the non-structural activities consume 60% of the total cost in the CFS case. Structurally, CFS is cheaper than RC by 13%. Doctolero and Batikha [44] estimated that the RC frame structure is 61% more costly than the CFS frame structure, but that was with respect to a studied four-storey building.

Table 13. Cost of construction with the inclusion of extra labour cost due to construction duration.

Construction method	Total Cost AED/m^2 (USD/m^2) Table 10	Total man hours (hr/m^2) Table 8	Extra/Saving man hours from 3DCP (hr/m^2)	Labor cost rate AED/hr (USD/hr)	Extra/Saving cost from 3DCP AED/m^2 (USD/m^2)	Final cost AED/m^2 (USD/m^2)
3DCP	954 (260)	9.8	0	22 (6)	0	954(260)
PMC	1361 (371)	2.7	-7.1		-156 (-42)	1205(328)
RC	820 (223)	20.8	11		242 (66)	1062(289)
CFS	945 (257)	17.7	7.9		174 (47)	1119(305)
HRS	1061 (289)	18.8	9		198 (54)	1259(343)

6.4. Influence of construction method on CO_2 emissions from material production

Figure 7 shows that 3DCP is the most sustainable construction technique, followed by CFS. PMC is the least sustainable, releasing 42% more CO_2 emissions than 3DCP. The RC and HRS structures produce 25% and 30% more CO_2 emissions, respectively. More concrete and primary steel (HRS and steel reinforcement) productions result in more CO_2 emissions. Therefore, lower CO_2 emissions are produced in the case of 3DCP, where there is no steel reinforcement in the printed walls. The same can be said for CFS sections that are made entirely of recycled material, like steel scrap and car junk.

Weng et al. [24] explored the CO_2 emissions of a 3DCP bathroom unit and found that it is 86% lower than a precast bathroom. Mohammad et al. [68] studied the conventional construction method of RC columns with masonry blocks compared to the 3DCP construction method and found that 3DCP can produce 22% lower CO_2 emissions than conventional RC construction. The same research demonstrated that adding more columns and beams to 3DCP causes the structure to release 29% higher CO_2 emissions than the RC structure, which, in turn, leads to an unsustainable design.

Many studies have highlighted the CO_2 emissions of concrete structures compared to the HRS technique. Structurally, both systems emit almost the same CO_2 [69] amounts, as confirmed in Table 12. After including the finishing, the RC structures produced 26-40% lower CO_2 emissions than HRS construction [69, 70]. In the current study, the RC building registered 4% lower CO_2 emissions than the HRS building (Figure 7; Table 12).

It is very rare to find a reliable comparison between a CFS structure and other building materials regarding CO_2 emissions. However, the market confirms the high sustainability of CFS, since it is composed of recycled material. In this research, CFS shows that in total, it emits 18% lower CO_2 emissions than RC (Figure 7). Structurally, CFS produces 46% lower CO_2 emissions than RC (Table 12), which indicates the effect of non-structural finishes on CO_2 emissions.

7. Conclusions

In this research, a two-storey building was designed using different construction methods to evaluate the efficiency of implementing 3DCP compared to other construction techniques in terms of building weight, construction duration, construction cost and CO_2 emissions. The following conclusions were obtained:

- Steel structures provide the lowest weight compared to other construction methods and were found to be 34% lighter than 3DCP structures. Precast modular concrete produces the heaviest weight and is 35% heavier than 3DCP structures. The cast-in-situ RC structure offers almost the same weight as 3DCP.
- Precast modular concrete is the fastest construction method and is 270% faster than 3DCP. This study also shows that 3DCP has a shorter construction duration than reinforced concrete and steel buildings by an average of 95%.
- Taking the reflection of construction duration on the construction cost, 3DCP offers the most economical construction solution. It is 21% cheaper than precast modular concrete and 10% cheaper than the RC building. 3DCP also cuts the cost by 15% and 24% when compared to cold-formed steel and hot-rolled steel respectively.
- This research shows that 3DCP and cold-formed steel are the most sustainable construction solutions. Precast modular construction brings the heaviest carbon emissions from material production and is 42% greater than 3DCP. In contrast, the cast-in-situ RC building produces 25% higher CO_2 emissions than 3DCP while hot-rolled steel construction increases CO_2 emissions by 30% when compared to 3DCP.

8. Work limitations and recommendations

As indicated in Section 4.2, the configuration of the 3D printed elements was selected according to industry practice because of the absence of a code of practice for designing 3DCP. Although some validations using the research data to confirm the structure's safety were performed for the assumed printed sections shown in Figure 2, this work is limited to the implemented 3DCP in the market. A future design standard code for 3DCP may require different configurations for the printed unreinforced element, which would, in turn, affect the total volume of printed concrete used, and hence, change the results obtained in this study. Therefore, a readjustment for the current work conclusions may be required when a design standard code for 3DCP is available.

Nevertheless, the present study highlights the potential of Unreinforced 3DCP in providing cheaper, faster, safer, and more sustainable construction solutions for low-rise buildings. Though, it must be noted that utilising steel reinforcement embedded in the printed elements, as is the case in the current market, may ruin this fact. Therefore, future research needs to support producing a standard for designing Unreinforced 3DCP, similar to the standards available for Unreinforced Masonry.

Moreover, researching and developing a printable concrete mixture that employs recycled materials will also reduce the cost and significantly improve the sustainability index of the construction technique.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

References

[1] United Nations (2019a). Population Facts: How certain are the United Nations global population projections?, Departments of Economic and Social Affairs, December 2019, No. 2019/6, New York. Available at: https://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2019-6.pdf (accessed: September 26, 2021).

[2] Research and Markets (2020). Global Construction Industry Databook Series - Market Size & Forecast by Value and Volume, Opportunities in Top 100 Cities, and Risk Assessment, Report ID: 5006112, Dublin. Available at: https://www.researchandmarkets.com/reports/5006112/global-construction-industry-databook-series (accessed: September 26, 2021)

[3] Ferdous W., Bai Y., Ngo T.D., Manalo A., Mendis P. (2019). New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review, Engineering Structures, 183, pp. 883–893. https://doi.org/10.1016/j.engstruct.2019.01.061

[4] United Nations (2019b). World Urbanization Prospects: The 2018 Revision, Departments of Economic and Social Affairs, ST/ESA/SER.A/420, ISBN: 978-92-1-148319-2, New York. Available at: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf (accessed: September 26, 2021)

[5] Elkaftangui, M. and Mohamed, B. (2018). Optimizing prefabricated construction techniques in UAE as a solution to shortage of middle-income housing, Proceedings of the 3rd International Conference on Design and Manufacturing Engineering, Materials Science, Engineering and Chemistry (MATEC Web of Conferences 221, 01006, Abu Dhabi, UAE, 29th-30th October, 4p. https://doi.org/10.1051/matecconf/201822101006

[6] Mália, M, de Brito, J, Pinheiro, M. and Bravo, M, (2013). Construction and demolition waste indicators. Waste Management & Research, 31(3), pp. 241-255. https://doi.org/10.1177/0734242X12471707

[7] Paul, S.C, Tay, Y.W.D., Panda, B., Tan, M.J. (2018). Fresh and hardened properties of 3D printable cementitious materials for building and construction, Archives of Civil and Mechanical Engineering, 18(1), pp. 311-319. http://dx.doi.org/10.1016/j.acme.2017.02.008

[8] Siddika A., Mamun Md. A., Ferdous W., Saha A.K., Alyousef R. (2020). 3D-printed concrete: applications, performance, and challenges, Journal of Sustainable Cement-Based Materials, 9(3), pp. 127–164. http://dx.doi.org/10.1080/21650373.2019.1705199

[9] Zhang J., Wang W., Dong S.,Yu X., Han B. (2019). A review of the current progress and application of 3D printed concrete, Composites Part A: Applied Science and Manufacturing, 125, 105533, 13p. https://doi.org/10.1016/j.compositesa.2019.105533

[10] Paul, S.C, Zijl, G.P.A.G., Tan, M.J., Gibson, I. (2018). A review of 3D concrete printing systems and materials properties: current status and future research prospects, Rapid Prototyping Journal, Emerald Publishing Limited [ISSN 1355-2546], 24 (4), pp.784–798. https://doi.org/10.1108/RPJ-09-2016-0154

[11] Pardo-Ferreira M.D.C., Rubio-Romero J.C., Gibb A., Calero-Castro S. (2020). Using functional resonance analysis method to understand construction activities for concrete structures, Safety Science, 128, 104771, 13p. https://doi.org/10.1016/j.ssci.2020.104771

[12] Jazayeri E., Dadi G.B. (2017). Construction safety management systems and methods of safety performance measurement: A review, Journal of Safety Engineering, Scientific & Academic Publishing, 6(2), pp. 15-28. https://doi.org/10.5923/j.safety.20170602.01

[13] Malaeb Z., AlSakka F. and Hamzeh F. (2019). 3D Concrete Printing: machine design, mix proportioning, and mix comparison between different machine setups, in: Sanjayan J., Nazari A. and Nematollahi B. (Eds), 3D Concrete Printing Technology: Construction and Building Applications, Butterworth-Heinemann, ISBN: 978-0-12-815481-6, pp. 115-136, UK. https://doi.org/10.1016/B978-0-12-815481-6.00006-3

[14] Kazemian A., Yuan X., Meier R. and Khoshnevis B. (2019). Performance-based testing of portland cement concrete for construction-scale 3D printing, in: Sanjayan J., Nazari A. and Nematollahi B. (Eds), 3D Concrete Printing Technology: Construction and Building Applications, Butterworth-Heinemann, ISBN: 978-0-12-815481-6, pp. 13-35, UK. https://doi.org/10.1016/B978-0-12-815481-6.00002-6

[15] Alhumayani H., Gomaa M., Soebarto V., Jabi W. (2020). Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete, Journal of Cleaner Production, 270, 122463, 13p. https://doi.org/10.1016/j.jclepro.2020.122463

[16] Hager I., Golonka A., Putanowicz R. (2016). 3D printing of buildings and building components as the future of sustainable construction?, Procedia Engineering, 151, pp. 292 – 299. https://doi.org/10.1016/j.proeng.2016.07.357

[17] Holt C., Edwards L., Keyte L., Moghaddam F., Townsend B. (2019). Construction 3D Printing, in: Sanjayan J., Nazari A. and Nematollahi B. (Eds), 3D Concrete Printing Technology: Construction and Building Applications, Butterworth-Heinemann, ISBN: 978-0-12-815481-6, pp. 349-370, UK. https://doi.org/10.1016/B978-0-12-815481-6.00017-8

[18] García de Soto, B., Agustí-Juan, I., Hunhevicz, J., Joss, S., Graser, K., Habert, G., Adey, B. (2018). Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall, Automation in Construction, 92, pp. 297-311. https://doi.org/10.1016/j.autcon.2018.04.004

[19] Tobi A.L.M., Omar S.A., Yehia Z., Al-Ojaili S., Hashim A., Orhan O. (2018). Cost viability of 3D printed house in UK, Proceedings of the 4th Asia Pacific Conference on Manufacturing Systems and the 3rd International Manufacturing Engineering Conference 7–8 December 2017, Yogyakarta, Indonesia, Institute of Physics (IOP) Conference Series: Materials Science and Engineering, 319, 012061, 7p. https://doi.org/10.1088/1757-899X/319/1/012061

[20] Gaudillière N., Duballet R., Bouyssou C., Mallet A., Roux P., Zakeri M., Dirrenberger J. (2019). Building applications using lost formworks obtained through large-scale additive manufacturing of ultra-high-performance concrete, in: Sanjayan J., Nazari A. and Nematollahi B. (Eds), 3D Concrete Printing Technology: Construction and Building Applications, Butterworth-Heinemann, ISBN: 978-0-12-815481-6, pp. 37-58, UK. https://doi.org/10.1016/B978-0-12-815481-6.00003-8

[21] BS EN 1991-1-1:2002 (2002). Eurocode 1: Actions on structures - Part 1-1: General actions — Densities, self-weight, imposed loads for buildings, British Standards Institution, ISBN: 978 0 580 66415 1, London, (accessed: December 10, 2020).

[22] NA to BS EN 1991-1-1:2002 (2002). UK National Annex to Eurocode 1: Actions on structures - Part 1-1: General actions — Densities, self-weight, imposed loads for buildings, British Standards Institution, ISBN: 978 0 539 05066 0, London, (accessed: December 10, 2020).

[23] Cobb F. (2015). Structural Engineer's Pocket Book: Eurocodes, CRC Press, Taylor & Francis Group, ISBN: 978-1-4665-5208-1, USA.

[24] Weng Y., Li M., Ruan S., Wong T.N., Tan M.J., Yeong K.L.O., Qian S. (2020). Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach, Journal of Cleaner Production, 261, 121245, 13p. https://doi.org/10.1016/j.jclepro.2020.121245

[25] BS EN 1992-1-1:2004 (2004). Eurocode 2: Design of concrete structures- Part 1-1: General rules and rules for buildings, British Standards Institution, ISBN: 978 0 580 83726 5, London, (accessed: December 10, 2020).

[26] BS EN 1996-1-1:2005 (2005). Eurocode 6 —Design of masonry structures- Part 1-1: General rules for reinforced and unreinforced masonry structures, British Standards Institution, ISBN: 978 0 580 72628 6, London, (accessed: December 10, 2020).

[27] Rahul A., Santhanam M., Meena H. and Ghani Z. (2019). Mechanical characterization of 3D printable concrete, Construction and Building Materials, 227, 116710, 12p. https://doi.org/10.1016/j.conbuildmat.2019.116710

[28] Baz B., Aouad G. and Remond S., (2020). Effect of the printing method and mortar's workability on pull-out strength of 3D printed elements, Construction and Building Materials, 230, 117002, 8p. https://doi.org/10.1016/j.conbuildmat.2019.117002

[29] Jianchao Z., Faried T.Z.M. and Wengang C. (2017). 3D printing cement-based ink, and it's application within the construction industry, Proceedings of the International Conference on Advances in Sustainable Construction Materials & Civil Engineering Systems, Sharjah, UAE. 18-20 April, Paper No. 02003, pp. 100-113. https://doi.org/10.1051/matecconf/201712002003

[30] Wolfs R., Bos F. and Salet T. (2019). Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion, Cement and Concrete Research, 119, pp. 132-140. https://doi.org/10.1016/j.cemconres.2019.02.017

[31] Alawneh M., Matarneh M., El-Ashri S., (2018). The world's first 3D-printed office building in Dubai. PCI/NBC, 9p. Available at: https://www.pci.org/PCI_Docs/Papers/2018/32_Final_Paper.pdf (accessed: September 26, 2021).

[32] BS 5950-5:1998 (2006). Structural use of steelwork in building- Part 5: Code of practice for design of cold formed thin gauge sections, British Standards Institution, ISBN: 0 580 28248 1, London, (accessed: December 10, 2020).

[33] Hussain Mohd. Abbas Block Factory, Hussain Mohd Abbas Block Factory-Catalogue, available at: http://www.hablocks.com/userfiles/Hussain-Mohd-Abbas-Block-Factory-catalogue.pdf (accessed: December 10, 2020).

[34] Knauf Factory, Knauf Price List 2020, available at: https://www.knauf.ae/literature/Knauf%20Price%20List%202020.pdf (accessed: December 10, 2020).

[35] ArcelorMittal. Steel Buildings in Europe, Multi-Storey Steel Buildings, Part 1: Architect's Guide, available at: https://constructalia.arcelormittal.com/en/news_center/articles/design_guides_steel_buildings_in_europe (accessed: December 10, 2020).

[36] Mahamid I (2016). Preliminary estimate for reinforcement steel quantity in residential buildings, Organization, Technology and Management in Construction, De Gruyter Open, 8, pp. 1405–1410. https://doi.org/10.1515/otmcj-2016-0006

[37] BS EN 1993-1-1:2005 (2005). Eurocode 3: Design of steel structures- Part 1-1: General rules and rules for buildings, British Standards Institution, London, (accessed: December 10, 2020).

[38] Thiruvengadam V., Wason J.C. and Gayathri L. (2004). Cost modeling of reinforced concrete buildings designed for seismic effects, Proceedings of the 13th World Conference on Earthquake Engineering, August 1-6, Paper No. 1956, Vancouver, B.C., Canada. Available at: https://www.iitk.ac.in/nicee/wcee/article/13_1956.pdf (accessed: September 26, 2021).

[39] Dhakal R.P., MacRae G.A., Pourali A. and Paganotti G. (2016). Seismic fragility of suspended ceiling systems used in NZ based on component tests, Bulletin of the New Zealand Society for Earthquake Engineering, 49(1), pp. 45-63. https://doi.org/10.5459/bnzsee.49.1.45-63

[40] Boafo F. E., Kim J.H. and Kim J.T. (2016). Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways, Sustainability, Molecular Diversity Preservation International (MDPI), 8, 558, 16p. https://doi.org/10.3390/su8060558

[41] Nematollahi B., Xia M. and Sanjayan J. (2017). Current Progress of 3D Concrete Printing Technologies, Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC 2017), 28

June – 1 July, ISBN: 978-80-263-1371-7, Taipei, Taiwan, pp. 260-267. https://doi.org/10.22260/ISARC2017/0035

[42] Zherebtsov N. (2020). The largest in the world 3D-printed building was made in Dubai, Manufacturing Tomorrow Magazine, available at: https://www.manufacturingtomorrow.com/article/2020/01/the-largest-in-the-world-3d-printed-building-was-made-in-dubai/14634 (accessed: October 16, 2021).

[43] Qureshi L.A., Shehzad A., Ejaz E. and Zaman F. (2013). Comparison of energy efficient cold rolls steel construction with the prevailing conventional construction, Proceedings of the International Conference on Sustainable Built Environment, Kandy, Sri Lanka, 14-16 December, 12p. Available at: http://dl.lib.uom.lk/bitstream/handle/123/8949/SBE-12-85.pdf?sequence=1&isAllowed=y (accessed: September 26, 2021).

[44] Doctolero L. and Batikha M. (2018). Using cold-formed steel section in buildings-comparative study, Proceedings of the 104th International Academy of Science, Technology, Engineering and Management (IASTEM) conference, Dubai, UAE, 1st-2nd February, 6p. Available at: https://www.worldresearchlibrary.org/up_proc/pdf/1384-15218771961-6.pdf (accessed: September 26, 2021).

[45] COBOD (2020). BOD2 Specifications, Available at: https://cobod.com/wp-content/uploads/2020/09/BOD2-Specifications-1.pdf. (accessed: March 10, 2021).

[46] Chan, T. and Aibinu, A. (2012). A comparison of construction cost and technology choice, Proceedings of the Management of Construction: Research to Practice Conference, 26-29 June, Centre Mont-Royal, Montreal, Vol.1, pp. 61-72. Available at: https://www.irbnet.de/daten/iconda/CIB_DC25599.pdf (accessed: September 26, 2021).

[47] Augur H. (2016). 3D Printed Office Building Unveiled in Dubai, All3DP, available at: https://all3dp.com/3d-printed-office-building/ (accessed: April 11, 2021).

[48] Nerella V.N., Krause M. and Mechtcherine V. (2020). Direct printing test for buildability of 3D-printable concrete considering economic viability, Automation in Construction, 109, 102986, 16p. https://doi.org/10.1016/j.autcon.2019.102986

[49] Lawson R.M. and Ogden R.G. (2010). Sustainability and process benefits of modular construction, Proceedings of the 18th International Council for Research and Innovation in Building (CIB), TG57-Special Track, CIB Publication 354, 10-13 May 2010 Salford, United Kingdom, pp. 38-51. Available at: https://www.irbnet.de/daten/iconda/CIB18783.pdf (accessed: September 26, 2021).

[50] Ahmed M.F., Rizwan S.H., Ahmed M.H., Batikha M. (2020). Using Recycled Waste Material from UAE in Concrete, Proceedings of the 3rd International Multi-Conference on Advances in Science and Engineering Technology, ASET'2020: Advanced Materials, Design and Manufacturing, The Higher Colleges of Technology (HCT), 4-6 February, Institute of Electrical and Electronics Engineers (IEEE), ISBN:978-1-7281-4641-6, Dubai, UAE, 6p. https://doi.org/10.1109/ASET48392.2020.9118367

[51] Batikha M., Ali S.T.M., Rostami A. and Kurtayev M. (2020). Using recycled coarse aggregate and ceramic waste to produce sustainable economic concrete, International Journal of Sustainable Engineering, 14(4), pp. 785-799. https://doi.org/10.1080/19397038.2020.1862353

[52] Mouna Y., Batikha M. and Suryanto B. (2021). Low carbon recycled aggregate concrete: roles of slag and silica fume, Proceedings of the 8th Zero Energy Mass Custom Home international conference (ZEMCH 2021), ISSN: 2652-2926, 26 – 28 October, United Arab Emirates University, Al-Ain, UAE, 11p., In press.

[53] Carpenter A. (2012). CO_2 abatement in the iron and steel industry, International Energy Agency (IEA) Clean Coal Centre, CCC/193 ISBN: 978-92-9029-513-6. Available at: https://usea.org/sites/default/files/012012_CO2%20abatement%20in%20the%20iron%20and%20steel%20industry_ccc193.pdf (accessed: September 26, 2021).

[54] World Steel Association (2019). World Steel in Figures 2019, Brussels, Belgium. Available at: https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf (accessed: September 26, 2021).

[55] Flint I.P., Allwood J.M. and Serrenho A.C. (2019). Scrap, carbon and cost savings from the adoption of flexible nested blanking, International Journal of Advanced Manufacturing Technology, 104, pp. 1171–1181. https://doi.org/10.1007/s00170-019-03995-6

[56] Broadbent C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy, International Journal of Life Cycle Assess, 21, pp. 1658–1665. https://doi.org/10.1007/s11367-016-1081-1

[57] Milford R.L., Allwood J.M. and Cullen J.M. (2011). Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminum sectors, Resources, Conservation and Recycling, 55, pp. 1185-1195. https://doi.org/10.1016/j.resconrec.2011.05.021

[58] Zhang Y., Zhang Y., Liu G., Yang Y., Wu M., Pang B. (2018). Fresh properties of a novel 3D printing concrete ink, Construction and Building Materials, 174, pp. 263-271. https://doi.org/10.1016/j.conbuildmat.2018.04.115

[59] Kruger J., Zeranka S., Zijl G.V. (2019). 3D concrete printing: A lower bound analytical model for buildability performance quantification, Automation in Construction, 106, 102904, 14p. https://doi.org/10.1016/j.autcon.2019.102904

[60] Rahul A.V., Santhanam M., Meena H. and Ghani Z. (2019). 3D printable concrete: Mixture design and test methods, Cement and Concrete Composites, 97, pp. 13-23. https://doi.org/10.1016/j.cemconcomp.2018.12.014

[61] Buildings Energy Data Book 2011 (2012), D&R International, Ltd., USA Department of Energy, Maryland, USA. Available at: https://ieer.org/wp/wp-content/uploads/2012/03/DOE-2011-Buildings-Energy-DataBook-BEDB.pdf (accessed: September 26, 2021).

[62] Ecofys (2012). Methodology for the free allocation of emission allowances in the EU ETS, Sector report for the gypsum industry, London, UK. Available at: https://ec.europa.eu/clima/system/files/2016-11/bm_study-gypsum_en.pdf (accessed: September 26, 2021).

[63] Philip A. M. and Kannan M.R. (2021). Constructability assessment of cast in-situ, precast and modular reinforced concrete structures, Materials Today: Proceedings, 45, pp. 6011-6015 https://doi.org/10.1016/j.matpr.2020.09.528

[64] Hossain M.A., Zhumabekova A., Paul S.C. and Kim J.R. (2020). A review of 3D Printing in construction and its impact on the labor market, sustainability, Molecular Diversity Preservation International (MDPI), 12, 8492, 21p. https://doi.org/10.3390/su12208492

[65] ArcelorMittal. Steel Buildings in Europe, Multi-Storey Steel Buildings, Part 2: Concept Design, available at: https://constructalia.arcelormittal.com/en/news_center/articles/design_guides_steel_buildings_in_europe (accessed: December 10, 2020).

[66] AECOM (2020). Middle East Property & Construction Handbook 2018/19, available at: https://www.aecom.com/ae/wp-content/uploads/2018/10/Construction-Handbook-2018_19.pdf (accessed: May 15, 2021).

[67] Abu-Hamd M. and Abouhamad M. (2019). Life cycle cost analysis of light steel framed building with cement-based walls and floors, Proceedings of the Canadian Society for Civil Engineering (CSCE) annual conference, 12 – 15 June, Montreal, Canada, 10p. Available at: https://www.researchgate.net/publication/339091257_LIFE_CYCLE_COST_ANALYSIS_OF_LIGHT_STEEL_FRAMED_BUILDINGS_WITH_CEMENT-BASED_WALLS_AND_FLOORS (accessed: September 26, 2021).

[68] Mohammad M., Masad E. and Al-Ghamdi S.G. (2020). 3D Concrete Printing Sustainability: A comparative life Cycle Assessment of Four Construction Method Scenarios, Buildings, Molecular Diversity Preservation International (MDPI), 10 (12), 245, 20p. https://doi.org/10.3390/buildings10120245

[69] Chae C.U., Lee K.H. and Jung S.C. (2005). Comparative study on the amount of CO_2 emission of building materials between reinforced concrete and steel structure buildings using input-output analysis, Proceedings of the World Sustainable Building conference, 27-29 September, Tokyo, pp. 1880-1883. Available at: https://www.irbnet.de/daten/iconda/CIB3782.pdf (accessed: September 26, 2021).

[70] Kim S., Moon J., Shin Y., Kim G. and Seo D. (2013). Life comparative analysis of energy consumption and CO_2 emissions of different building structural frame types, The Scientific World Journal, Hindawi Publishing Corporation, volume 2013, 175702, 5p. http://dx.doi.org/10.1155/2013/175702

[71] De Schutter G., Lesage K., Mechtcherine V., Nerella V.N., Habert G., and Agusti-Juan I. (2018). Vision of 3D printing with concrete — Technical, economic and environmental potentials, Cement and Concrete Research, 112, pp.25-36. https://doi.org/10.1016/j.cemconres.2018.06.001

[72] Bhattacherjee S., Basavaraj A. S., Rahul A.V., Santhanam M., Gettu R., Panda B., Erik Schlangen E., Chen Y., Copuroglu O., Ma G., Wang L., Beigh M.A.B., Mechtcherine V. (2021). Sustainable materials for 3D concrete printing, Cement and Concrete Composites, 122, 104156, 14p. https://doi.org/10.1016/j.cemconcomp.2021.104156

[73] Batikha M. and Alkam F. (2015). The effect of mechanical properties of masonry on the behavior of FRP-strengthened masonry-infilled RC frame under cyclic load, Composite Structures, 134, pp. 513–522. http://dx.doi.org/10.1016/j.compstruct.2015.08.105

[74] Shahzada K., Khan A.N., Elnashai A.S., Ashraf M., Javed M., Naseer A. and Alam B. (2012). Experimental seismic performance evaluation of unreinforced brick masonry buildings. Earthquake Spectra, 28(3), pp.1269–1290. https://doi.org/10.1193/1.4000073

[75] Losanno D., Ravichandran N., Parisi F., Calabrese A. and Serino G. (2021). Seismic performance of a low-cost base isolation system for unreinforced brick masonry buildings in developing countries, Soil Dynamics and Earthquake Engineering, 141, 106501, 17p. https://doi.org/10.1016/j.soildyn.2020.106501

[76] ASCE (2010). Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Virginia, ISBN: 978-0-7844-1085-1, USA, (accessed: December 10, 2020).