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Selecting the Best 3D Concrete Printing Technology for Refugee Camp's Shelter Construction Using Analytical Hierarchy Process: The Case of Syrian Refugees in Jordan

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Abstract: Upgrading the Syrian refugee shelter design serves humanitarian needs, especially since the currently used T-shelters have a life span of 2–4 years, and there are no clear signs of an imminent return of Syrian refugees to their country, even after the end of the civil war. The use of 3D concrete printing can provide a promising method to construct new durable shelters with a long life span and provide better protection against extreme change in the desert climate, privacy, and cultural constraints. This research aims to use multi-criteria decision methods—in particular, the Analytical Hierarchal Process (AHP) method—to select the best 3D concrete printing to construct these shelters. The proposed model takes the following into consideration: the machine's technical characteristics, building structure characteristics, and economic and environmental aspects. The three basic developed technologies—contour crafting, D-shape, and concrete printing—were used as alternatives in the model. The results show that contour crafting is the best technology for this application, and the inconsistency test and sensitivity analysis indicate an effective and reasonable technology ranking.

Keywords: 3D concrete printing; refugee shelter; decision-making; contour crafting; concrete printing; D-shape; AHP

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1. Introduction

Jordan is one of the countries in the world that received the most refugees in the last century because of its geographical location within a region rife with conflicts. It became an asylum for Syrian refugees by virtue of its neighboring position: there are ten camps for Syrian refugees in Jordan, the most important of which are the Azraq and Zaatari camps [1–3].

The shelters in which the Syrian refugees live in Zaatari and Azraq suffer from many problems, as the current design does not provide enough space commensurate with the size of families, lacks the privacy imposed by culture and religion, and has a default age of two to four years. The conditions that resulted from the civil war in Syria forced these refugees to stay in refugee camps [4,5].

A rapidly emerging technology, 3D concrete printing, has attracted a lot of attention in recent years due to its potential to revolutionize the construction industry by producing layer-by-layer complex geometries with greater precision and speed using cementitious materials [6,7]. The 3D-printed concrete shelters provide more safety from fire, improved structure durability, enhanced long-term stability, better energy efficiency, and thermal insulation, and most importantly, speed of construction with reduced man-made errors when compared with traditional shelters [8,9].

The three basic developed 3D concrete technologies are contour crafting, D-shape, and concrete printing, and these methods differ among themselves in their technical characteristics and the produced structure [10]. Therefore, it is necessary to select the best technology that enables new shelters to be built with the minimum cost, the shortest time, and the least amount of materials and have the maximum benefits in terms of economic, humanitarian, and environmental aspects, especially in cold areas or refugee camps in conflict zones.

The AHP method is a well-known, simple, and effective methodology that breaks down a complex, multi-criteria decision problem into a system of hierarchies [11]. This study aims to use the AHP decision-making method to determine the best way to build a house that suits the needs of Syrian refugees in Jordan. The proposed model takes into consideration the machine's technical characteristics, building structure characteristics, economic aspects, and environmental aspects. This article is designed to present the most prominent challenges and problems that exist in the shelters currently in use, and then propose a new design aimed at addressing these problems through the use of the 3D concrete printing approach due to the economic and environmental advantages of this technology. Finally, the article proposes a simple decision model that helps in choosing the right technology among the different 3D concrete printing technologies presented.

2. Refugees Shelter Weakness and Proposed Solutions

2.1. The Current Used Shelter

The T-shelter was created for the Azraq camp to house Syrian refugees in Jordan. T-shelters are interlocking steel buildings with aluminum foam insulation sandwiched between two layers of IBR (inverted box rib) cladding. The T-shelters offer protection from brisk winds, dust, and abrupt climate changes. They are simple to transport and assemble because the steel parts, cladding, insulation, and other accessories are brought to the site in the form of a kit. After the structure is put in place, the reinforced concrete flooring is poured, with the option of including a side entry for more privacy. The shelter has a 24 m^2 surface area, a 2- to 4-year life span, and a total estimated cost of $3442. Figure 1 displays the currently used shelter at Azraq camp [12]. The main materials that are used to build different parts of a T-shelter include the following:

- Interlocking steel tubes that make up the structure;
- A door, which is covered in flat corrugated iron sheeting and insulated with 1.5 cm thick expanded polyethylene;
- Steel window frame with two 180-degree opening window wings, 90 cm wide and 89 cm high, painted white.
- Aluminum foam insulation for the walls and roof (15 mm thick Expanded Polyethylene), which is securely stretched and fastened to the shelter's exterior frame with self-driving screws;
- Reinforced concrete flooring (5 cm minimum thickness, reinforced with 6mm rebar, 30 cm spacing).

Figure 1. The currently used shelter at Azraq camp, adapted from Ref. [12].

2.2. Current T Shelter Weakness

Recent studies have evaluated the main issues, the refugees' concerns, and the problems in the sheltering camps faced by the occupants [4,5]. The studies have indicated the main weaknesses of shelters in the Zaatari and Azraq camps, which include the presence of flaws in the structure at the wall-roof junctions, which causes significant problems with the quality and results in serious health problems for the occupants due to water leakage and air penetration. Some of the refugees residing in the shelters connect two shelters using corrugated sheets covered in fabric. The extra room is used to accommodate the cultural and religious needs of the refugees, such as creating separate sleeping areas for men and women. The additional space is also used for socializing. The shelter floor is made of a timber base, which performed poorly against ingress water during the rainy season, resulting in musty loose floors that rodents easily gnawed through.

The Zaatari refugee shelter lacks a small outdoor area that gives female residents more freedom to go about their daily activities, such as collecting water, dishwashing, and watering plants. In Azraq Camp, personality and privacy are currently achieved by closing the windows in most occupied shelters, which is a religious requirement for camp residents. However, closing the windows limits ventilation and sunlight [4,5].

2.3. Proposed Shelter

After researching and examining the current refugee shelters in Al-Zatarri and Azraq, it is completely obvious that these facilities have weaknesses that endanger the residents' security, stability, and ability to practice their religion. The current shelters are overcrowded: their built capacity is only four inhabitants, which is smaller than the average size of a Syrian refugee family. Shelters do not have adequate thermal insulation, as well as they do not have social space, access to amenities, adequate ventilation, structural stability, safety, and privacy [4,5]. In addition, they lack space for religious rituals and do not provide a modernized sheltering environment, compared with the minimum living standards of the international community [13]. Although the designed life span of these shelters is 2–4 years, they have been used for more than 10 years, and there are no clear signs of an imminent return of Syrian refugees to their country, even after the end of the civil war [1].

Therefore, there is an urgency to find a new type of shelter that can guarantee proper shielding against extreme changes in the desert climate during the summer and winter in the camp. The life span of the camp outlives the usefulness of the current shelters, necessitating multiple shelter replacements over the course of the camp's existence. Therefore, a different approach that takes into account the robustness of the shelter and overcomes its current weaknesses will make a remarkable contribution to addressing the housing needs of refugees. An L-shaped shelter that was previously used in Iraq to host the refugees was selected as a potential solution that surpasses most of the drawbacks and limitations of the currently used shelters in Al-Zatarri and Azraq. Each shelter has two rooms, a kitchen, and a bathroom, and is designed to house one family. Figure 2 shows the views and the model for this shelter [12].

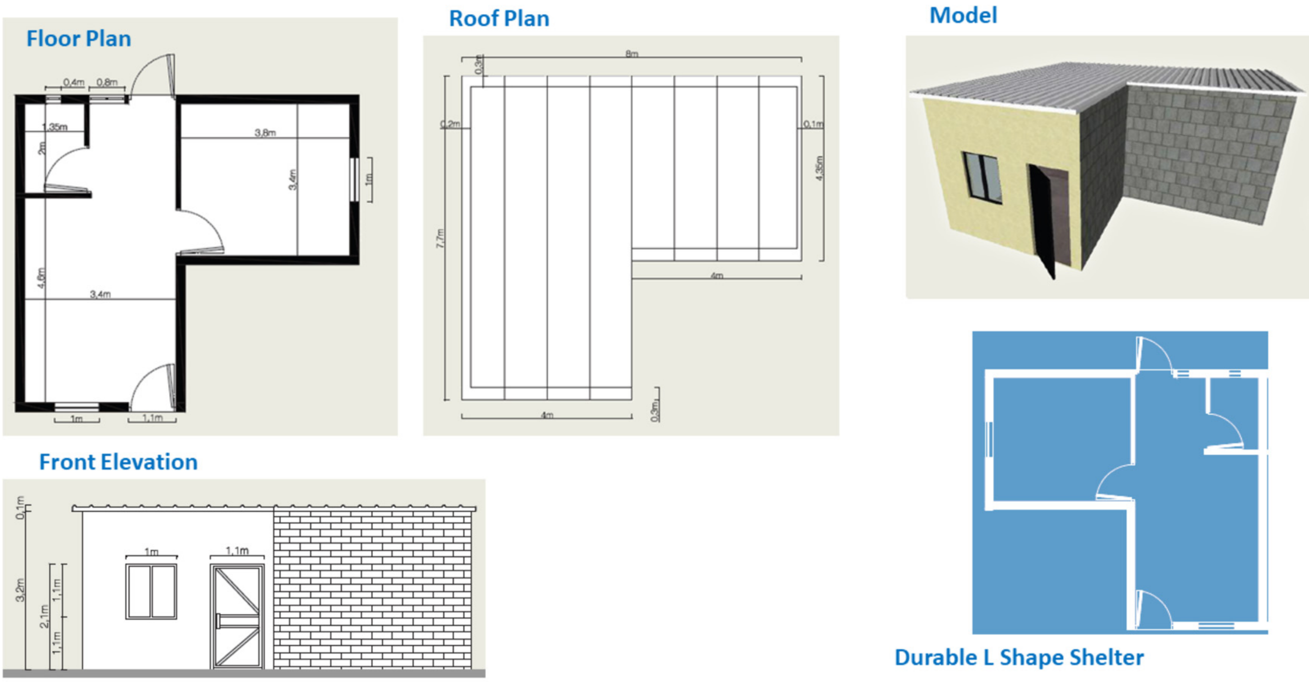


Figure 2. The views and the model for the suggested durable L shape shelter, adapted from Ref. [12].

2.4. Sheltering Camp Solutions

The proposed technology to construct refugee shelters is a 3D printing method using local materials. The use of this technology will guarantee that the 3D-printed shelters for international refugees built by humanitarian organizations are cost-effective and more affordable when compared with prefabricated cabins over time [14]. A concrete structure can last for 20 to 30 years, whereas a typical caravan would only last for four years [14]. The 3D-printed concrete shelters provide more safety from fire, improved structure durability, enhanced long-term stability, better energy efficiency, and thermal insulation, and most importantly, speed of construction with reduced man-made errors when compared with traditional shelters, as 3D printing technology requires two operators to construct the shelter's main structural components. Furthermore, after refugees leave, printed shelters may be used to provide housing for low-income residents of the hosting countries, The printable shelters could also be sufficiently improved to be turned into resorts or stores.

3. Selection of Decision Model

In this study, the AHP model was employed to choose the best 3D concrete printing method to construct refugee shelters out of the three famous technologies using "Expert Choice" software. Based on the weight assigned to each of the four main criteria mentioned in the next sub-section, a decision was made.

3.1. Selection Criteria

The processing parameters of 3D concrete printing machines play a crucial role in determining the characteristics of the final structure. Printing speed and layer thickness are among the most important processing parameters that affect the accuracy, surface quality, resolution, and mechanical properties of the printed structure [15,16]. Therefore, considering these parameters is essential for selecting 3D concrete printing technology.

Printing speed directly affects the build rate of the structure. Increasing printing speed reduces the amount of material extruded under the same extrusion pressure. The volume and number of interlayer pores increase, which causes delamination and results in a decrease in the accuracy of the printed structure and the printing quality [17]. Additionally, the printed material gradually narrows, the print's height and width decrease as the velocity increases, and the overall shape becomes trapezoidal [18]; whereas at low printing speeds, interlayer cracks are less noticeable and are more similar to specimen layer pores, which leads to better accuracy, surface quality, and improves the interlayer bonding strength of the printed structure [17,19]. The effect of printing speed on various mechanical properties of the printed structure has been extensively investigated. The studies showed that increasing printing velocity led to a decrease in compressive strength [20], flexural strength [21], tensile strength of the printed structure [18], and surface roughness, which in turn improved the overall aesthetic appeal and functionality of the printed structure [19], and resulted in higher porosity levels [17]. In contrast, reducing printing velocity improved the compressive strength [20] and the interlayer bonding strength [17], which in turn improved the overall flexural strength of the printed structure [21] and the tensile strength [16,22].

Printed layer thickness is another important processing parameter in 3D concrete printing as it affects the resolution and quality of the printed structure. A study showed that increasing layer thickness led to a decrease in the accuracy and surface quality of the printed structure. On the other hand, reducing layer thickness improved the resolution and quality of the printed structure, as shown in a study by [23].

Taking the above into consideration, the choice of a 3D concrete printer in this study is based on four main categories: machine characteristics, building structure characteristics, economic factors, and environmental factors. The printing speed, maximum operational area, printer layer thickness, and resolution make up the machine characteristics class. Mechanical characteristics, the utility of adding conduits, and the maximum height of printed walls are all included in the building structure characteristics class. The economic characteristics are made up of capital costs, raw material costs, and maintenance costs. The final category is "environmental impact", which has two subcategories: "power consumption" and "material waste". These requirements and their corresponding definitions are listed in Table 1.

Table 1. List of 3D concrete printer selection criteria and definitions.

Criteria	Sub-Criteria	Description
Machine characteristics	Printing speed	Maximum movement speed in the horizontal direction (mm/s).
	Maximum operational area	A maximum size of the building structure that can be printed by a particular 3D concrete printer and encompasses all of the design.
	Printing layer thickness	Maximum height of the extruded concrete layer in each path travel.
	Resolution	The smallest detail or minimum feature size that can be built.
Building structure characteristics	Mechanical properties	The mechanical performance of the produced structure, including compressive strength and interlayer bonding between extruded layers.
	Ability to add utility conduits	The possibility of laying out the utility conduits (i.e., electrical, plumbing, sewage, HVAC work, and insulation) within the walls during printing.
	Printed wall maximum height	The maximum height of stable structure that can be produced by the printer.
Economic impact	Capital cost	One-time expenses paid to the manufacturer to purchase the 3D printer, as well as additional expenses incurred to set up the facility to lay out the printer.
	Maintenance cost	The costs related to maintaining the printer's condition through routine maintenance and repairs as needed.
	Raw materials cost	The cost of startup materials used in the printed structure.
Environment impact	Power consumption	The electrical energy per unit time, required to operate the 3D printer.
	Materials waste	The amount of waste or unused redundant material incurred after 3d printing.

3.2. Candidates 3D Construction Technologies

3.2.1. Contour Crafting (CC)

The contour crafting (CC) technique is a 3D concrete printing to produce large-scale objects with a smooth finished surface [8]. Concrete extrusion and deposition are the foundation of CC. After the printer first prints the component's outer edge to create a closed section, the concrete material is poured into this section for further construction. CC can print using various materials on the same component. Different materials are delivered into the CC nozzle system and mixed there under computer control. After the concrete is forced out of the nozzle, the special CC trowel will shape it into a smooth, extremely accurate surface. The conduits for electrical, plumbing, and air conditioning can be embedded in the components. The CC process also has the ability to deflect the nozzle to create non-orthogonal surfaces, such as domes and vaults [10,24].

3.2.2. D-Shape

The D-shape method is based on injecting the binder into the surface of the material. This is designed to print artwork using 5–10 mm layers of an inorganic sand binder [25]. This system's printing head has several nozzles and can spread both the chemical agent and the solid powder. First, the printing head evenly distributes the powder layer's thickness, and the rolling cylinders apply homogeneous pressure to the powder layer. After the predetermined location, the chemical agent is then sprayed on the powder layer.

3.2.3. Concrete Printing (CP)

The print head for concrete printing for cement mortar extrusion is mounted on top of the crane. The concrete materials are continuously extruded while the printing nozzle follows a predetermined path. When compared with contour crafting, which allows for better control of complex geometries, the 3D CP process has a lower deposition resolution.

4. Selecting Using the AHP Model

The AHP selection model was conducted in seven steps: hierarchal model construction, main criteria pairwise comparison, sub-criteria pairwise comparison, alternative pairwise comparison, consistency testing, alternative total weight computation, overall ranking determination, and finally sensitivity analysis. The descriptions of these steps are presented in the following sections.

4.1. Model Construction

The aforementioned selection criteria that were presented in Section 3.1 are arranged in the hierarchal structure shown in Figure 3. The prescribed objective of the decision selection model is placed at the top level of the hierarchal model. The four main criteria come at the second level, and they act as parents for their sub-criteria that appear at the third level of the hierarchy. Last, the three alternative printing methods are positioned at the lowest level.

4.2. Criteria Pairwise Comparison

In this step, the four main step criteria are pairwise compared in terms of their importance with respect to the model goal [11] and the preference scale is utilized to create the pairwise differentiation matrix. The building structure characteristics are the most important criteria as they concern the ability to insert utility conduits within the wall during printing and mechanical properties, i.e., tensile strength and flexural strength. The building structure has a 40% influence on the decision. The machine's technical characteristics rank second, and they weigh 30% of the decision. Figure 4 shows a bar diagram of the relative significance of 3D concrete printer selection criteria and the pairwise comparison matrix, respectively. Also, in Figure 4b, the text in the cell is colored black to indicate that the criterion in the corresponding column is more significant than the criterion in the corresponding raw by the indicated number of times, and the text is colored red to indicate that the corresponding column is less significant than the criterion in the corresponding raw by the indicated number of times. For example, the yellow cell in the comparison matrix indicates that machine technical characteristics are 1.33 less important than building structure characteristics in their significance with respect to selecting the best 3D concrete printing.

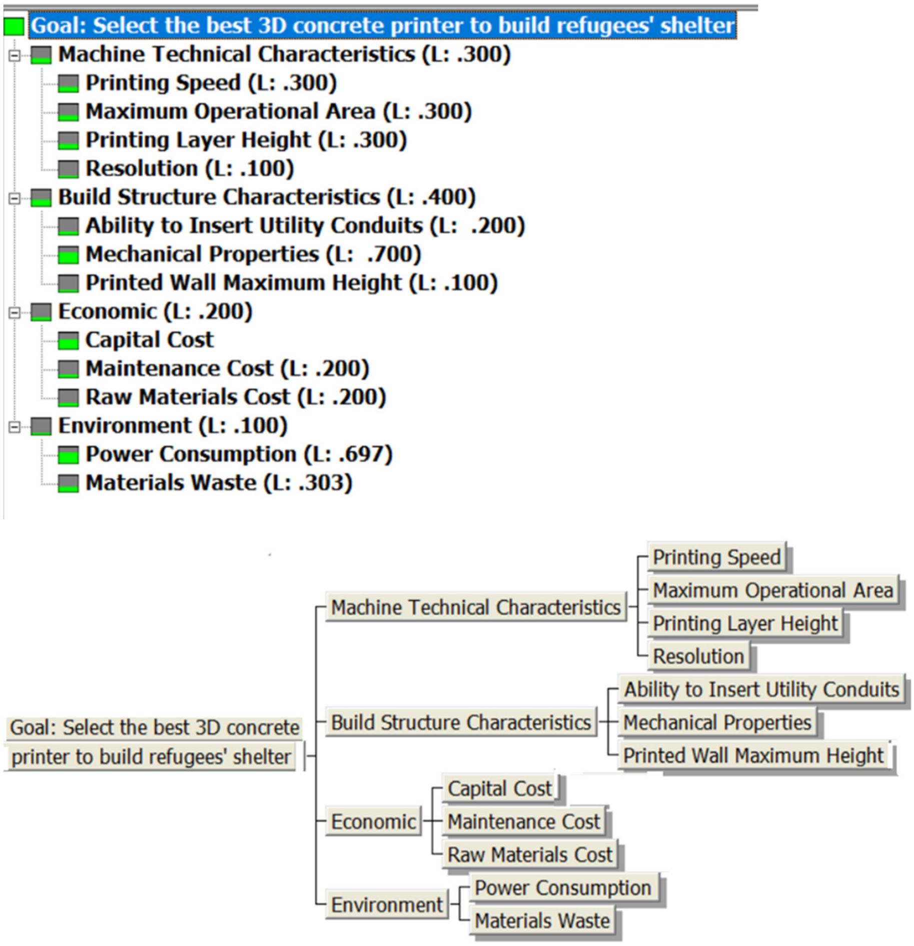
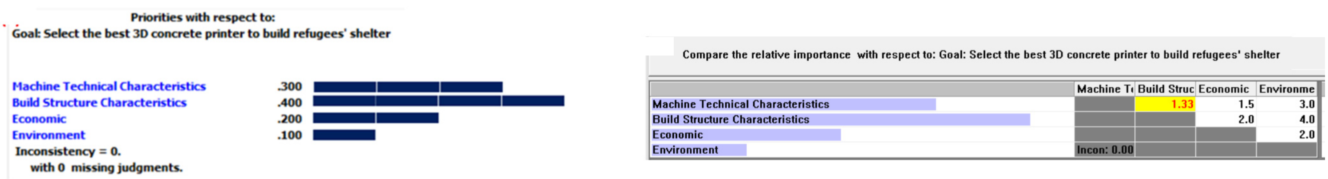


Figure 3. AHP decision hierarchy chart for selecting the best 3D concrete printer to build refugee shelters.



(**a**) (**b**)

Figure 4. Criteria for 3D concrete printer selection: (**a**) the bar diagram that shows the relative importance of 3D concrete printer selection criteria; (**b**) the pairwise comparison matrix for the main criteria for 3D concrete printer selection.

4.3. Sub-Criteria Pairwise Comparison

The sub-criteria for each one of the main four classes were pairwise compared against each other in terms of their importance to the parent criterion. Figure 5 shows the pairwise comparison matrices for the main class (parents) sub-criteria.

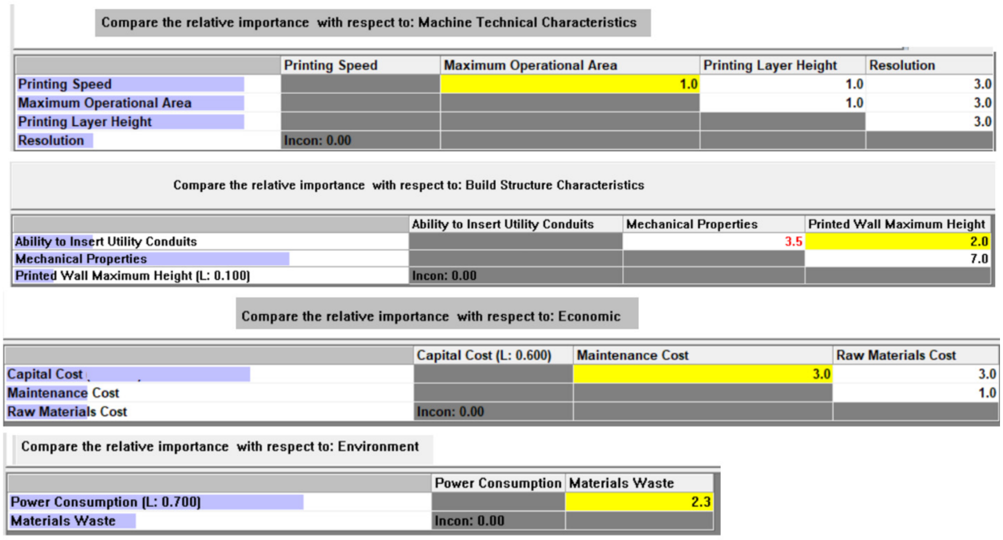


Figure 5. The pairwise comparison matrices for the main class (parents) sub-criteria.

4.4. Alternative Pairwise Comparison

According to the comparisons (criteria) used in the suggested decision-making model, Table 2 compares various types of printers. The third column is added to the table so that the two terms, "maximize and minimize", are used for the comparison aspects that should be high and low, respectively, in order to achieve the desired goal, which calls for some of the comparison aspects in the printer to be high and others to be low.

Table 2. Selection criteria for the 3D concrete printing to construct shelter for Syrian refugees and the required direction of change for each criterion.

Criteria (C)	Sub Criteria (CS)	Required Direction of Change	3D Concrete Printing Technology		
			Contour Crafting	D-Shape	Concrete Printing
Machine technical characteristics (C1)	Speed printing (CS11)	Maximize	Low	Medium	High
	Maximum operational area (CS12)	Maximize	Large scale structure	Medium size structure (limited frame 6 m × 6 m × 6 m)	Large scale structure
	Printing layer thickness (CS13)	Maximize	13 mm	5–25 mm	4–6 mm
	Resolution (CS14)	Maximize	Low (15 mm)	Low (9–20 mm)	High (0.13 mm)
Building structure characteristics (C2)	Printed wall maximum height (CS21)	Maximize	High (3.3 m)	Medium (2 m)	Medium (2 m)
	Ability to insert utility conduits (CS22)	Maximize	High (easy)	Low	Low
	Mechanical properties (strength) (CS23)	Maximize	Low bonding between layers	High strength	High strength
Economic (C3)	Capital cost (CS31)	Minimize	Medium	Low	High
	Maintenance cost (CS32)	Minimize	High (extrusion)	Low (spreading)	High (extrusion)
	Raw material cost (CS33)	Minimize	Low (cementitious or mortar)	High (powder materials and chemical agents)	Medium (mixed 3D-printed concrete)
Environment (C4)	Power consumption (CS41)	Minimize	High	Low	Medium
	Materials waste (CS42)	Minimize	Low	High (massive powder and redundant powder materials are needed to remove)	Medium

The comparisons between the three types of 3D concrete printers have been conducted in two steps:

- Step 1: Numbers 3, 6, or 9 are assigned for each alternative on each of the comparison aspects, where 3 is assigned for the alternative that has the lowest performance in a particular comparison aspect compared with the other alternatives. Numbers 6 and 9 are assigned for the alternatives that have the middle and highest performance in this comparison aspect compared with other alternatives. It should be noticed that the printed layer thickness, resolution, and maximum wall height criteria have the same numbers reported in Table 2. Table 3 summarizes the numbers assigned to each sub-criteria that were used to conduct alternative pairwise comparisons.

Table 3. Summary of the numbers assigned to each sub-criteria that were used to conduct the alternative pairwise comparison.

Criteria (C)	Sub Criteria (CS)	3D Concrete Printing Technology		
		Contour Crafting	D-Shape	Concrete Printing
C1	CS11	3	6	9
	CS12	9	6	9
	CS13 [1]	13	15	5
	CS14 [1]	15	14.5	0.13
C2	CS21	3.3	2	2
	CS22	9	3	3
	CS23	3	6	6
C3	CS31	6	3	9
	CS32	3	9	3
	CS33	9	3	6
C4	CS41	9	3	6
	CS42	3	9	6

[1] Numbers represent the average printing layer thickness and resolution for the corresponding printing methods.

As shown in Table 2, the printing speeds of these three methods that provide the best mechanical properties are different among methods. Concrete printing can be used at higher speeds compared with the other two methods. It is followed by the D-shape method, whereas contour crafting runs at the lowest speed. In addition, a higher printing speed implies less time to build the structure. Accordingly, higher printing speeds are more favorable than lower speeds regarding the achievement of the desired goal. In terms of printer operational area, both contour crafting and concrete printing can be used to build large-scale structures, which provides more flexibility to deal with great shelter sizes, whereas the use of the D-shape is often limited to medium-size structures. The construction time (T) relies on the number of layers within the wall (n), the time to create one layer (t_L), the traveling printing speed (v), the printed layer thickness (thk_L), the maximum wall height (MWH), and the perimeter of one layer (P) as evident by Equations (1)–(4).

$$T = n\ t_L, \tag{1}$$

$$n = (MWH)/(thk_L), \tag{2}$$

$$t_L = P/v, \tag{3}$$

$$T = (MWH\ P)/(thk_L\ v), \tag{4}$$

Studies show that the maximum stable layer height that can be produced by the contour crafting and D-shape is higher than the height that can be produced by the concrete printing method. Thus, contour crafting and D-shape are preferable to concrete printing regarding this criterion. On the other hand, the concrete printing method produces high resolution compared with the other two methods, contour crafting and D-shape. Contour crafting has a big advantage over the other two methods, as contour crafting supports the ability to lay out conduits (i.e., electrical, plumbing, sewage, HVAC work, and insulation) within the walls during printing. The method of printing has a direct bearing on the cost of maintenance because extrusion-based printers require more maintenance, which increases the cost. The D-shape printer, which uses spreading technology, is less expensive because it needs fewer repairs.

- Step 2: The relative importance index ($RII_{A,B}$) between any two alternatives A and B for each comparison aspect is computed using Equation (5), and the corresponding assigned numbers listed in Table 3, (φ_A and φ_B represent the assigned numbers for alternatives A and B in terms of comparison aspect φ, respectively):

$$RII_{A,B} = \varphi_A / \varphi_B, \tag{5}$$

Figure 6 shows the pairwise comparison matrix for all alternatives and criteria.

Alternative	Pairwise Machine Technical Characterist Printing Speed (L: .300)	Pairwise Machine Technical Characterist Maximum Operational Area (L: .300)	Pairwise Machine Technical Characterist Printing Layer Height (L: .300)	Pairwise Machine Technical Characterist Resolution (L: .100)	Pairwise Build Structure Characteristic Ability to Insert Utility Conduits (L: .200)	Pairwise Build Structure Characteristic Mechanical Properties (L: .700)	Pairwise Build Structure Characteristic Printed Wall Maximum Height (L: .100)
☑Contour Crafting	.333	1.000	1.000	.009	1.000	1.000	1.000
☑D-Shape	.667	.667	.956	.009	.333	1.000	.667
☑Concrete	1.000	1.000	.350	1.000	.333	.500	.667

Alternative	Pairwise Economic Capital Cost (L: .600)	Pairwise Economic Maintenance Cost (L: .200)	Pairwise Economic Raw Materials Cost (L: .200)	Pairwise Environment Power Consumption (L: .697)	Pairwise Environment Materials Waste (L: .303)
☑Contour Crafting	1.000	.333	1.000	1.000	1.000
☑D-Shape	.794	1.000	.333	.333	.146
☑Concrete	.420	.333	.667	.667	.382

Figure 6. The pairwise comparison matrix for the alternatives for all criteria.

4.5. Inconsistency Test

The rate of consistency is less than 0.1. This shows that the ranking of the printing methods is effective and the multi-criteria matrix is reasonable.

4.6. Alternative Final Rank Determinations

The net weight of each of the three alternatives is determined after building the AHP comparison matrices for the criteria, sub-criteria, and 3D concrete printing methods and is recorded in Table 4. The results show that contour crafting is the best 3D printing method to build refugee shelters. Figure 7 shows the final ranking of the three alternatives.

Table 4. Summary of weight factors for both criteria and alternatives.

3D Concrete Printing Technology	Building Structure Characteristics (L: 0.400)	Economic (L: 0.200)	Environment (L: 0.100)	Machine Technical Characteristics (L: 0.300)	Total
Contour Crafting	0.183	0.079	0.46	0.096	0.265
D-Shape	0.152	0.068	0.013	0.095	0.404
Concrete Printing	0.088	0.041	0.026	0.11	0.328

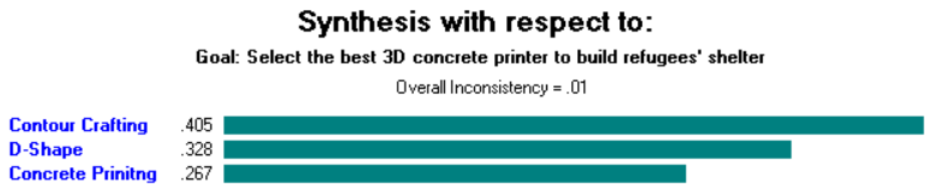


Figure 7. The final ranking of the AHP selection for the best 3D printing methods to build refugee shelters.

4.7. Sensitivity Analysis

The sensitivity analysis was carried out to investigate and assess the stability of the alternative ranking when the weights were changed. The weights assigned for the main parents' criteria and their child sub-criteria served as the baseline for this test. Then, several scenarios were generated using Expert Choice software, where in each scenario, the weight of one criterion was increased, and the alternative ranking was then updated. Figure 8 shows the sensitivity analysis of the examined AHP model. The analysis demonstrates that the rank attained does not change upon changing the weight of the criteria. This is a clue that the developed selection model is robust, as any possible minor changes in the weights of the criteria by the expert will not have a direct impact on the final decision.

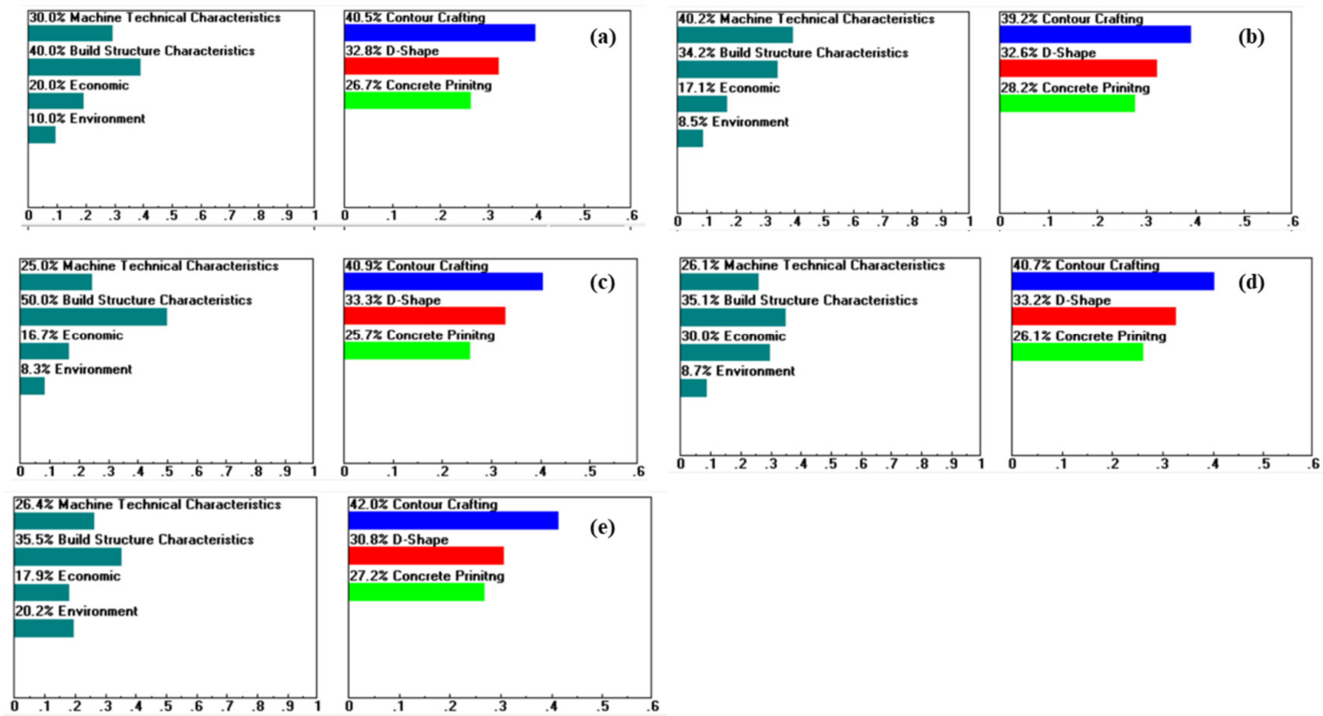


Figure 8. Sensitivity analysis of the AHP model for selecting the best 3D concrete printing methods to construct Syrian refugee shelters in Jordan: (**a**) baseline scenario; (**b**) machine technical characteristics increased by 10%; (**c**) building structure characteristics increased by 10%; (**d**) economic impact increased by 10%; (**e**) environment impact increased by 10%.

5. Cost and Feasibility Analysis of the Proposed Technology

A doctorate thesis in civil engineering at Swinburne University of Technology, Australia, addresses the feasibility of using 3D printing technology in the Middle East (ME) to build refugee shelters [9]. The current study relies on the results of that study to prove the cost efficiency of 3D printing technology over other traditional shelter types. The study compared the cost of printed shelters over other traditional methods, including steel and timber shelters, tents, and prefabricated caravans. Figure 9 shows the different types of shelters that were compared with respect to construction costs over the camp's life span.

To determine how practical and affordable 3D printing technology may be for building shelters in the ME, the construction cost of a whole printable camp was studied.

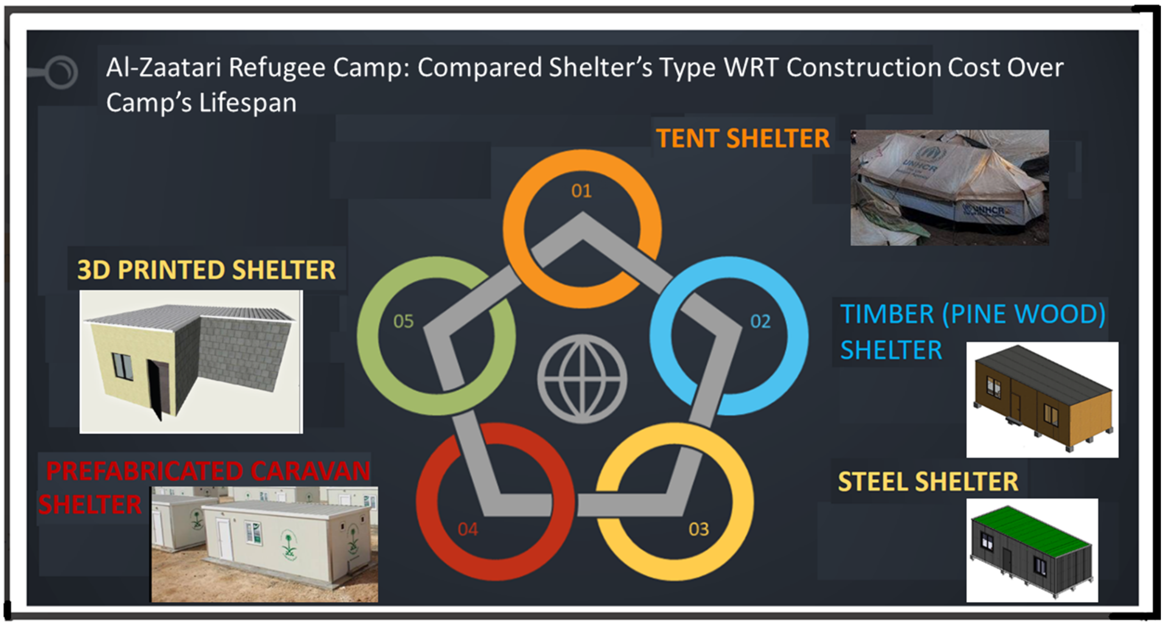


Figure 9. Compared different shelter types with respect to their construction costs over the camp's life span.

5.1. Construction Cost Estimation Model

To estimate the construction cost of each type of shelter over the camp's life span, a five-step procedure was followed, as shown in Figure 10. The calculations are based on the assumption that the camp was designed to host 80,000 refugees and that the life span of the camp was 15 years. Printer assembly and dismantling time were estimated based on the printer speed and the time required to build a single shelter. It was estimated that 25 printers were required to build the camp within two years using a single control point that connected one shelter to another with a fixed spacing distance, which minimized the need for continuous surveying onsite. For each shelter type, the researcher took into account the cost of a single shelter, durability under extreme climate conditions, such as heavy rain in the winter and high temperatures in the summer, single shelter occupancy capacity, and the necessary number of shelters to house camp refugees annually, as well as the number of necessary replacements over the course of the camp's life span and the total cost over a 15-year life span.

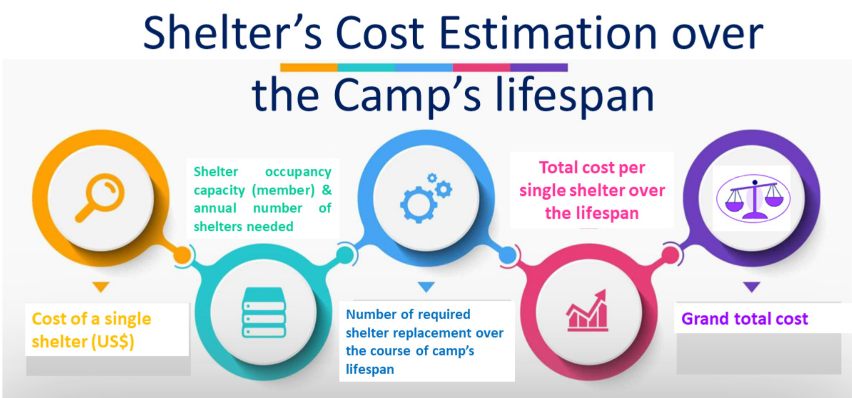


Figure 10. A five-step procedure that was followed to estimate the cost of each shelter type over the camp's life span.

5.2. Cost Efficiency

The necessary information that was used to estimate the total cost of each type of shelter over the camp's life span is summarized in Table 5. The used approach reveals that using the 3D-printed shelters for the Al-Zaatari camp could save a significant amount of money over other types to host the same number of refugees over the same period. For example, the saving of USD 118 million over 15 years between the 3D-printed shelter and the steel shelter results in a cost efficiency of 45% [9]. The cost efficiency of the 3D-printed shelters over other types of shelters is computed as the ratio between the savings achieved and the cost of a particular type of shelter and is presented in the last column of Table 5.

Table 5. Summary of the necessary information required to estimate the total cost of each shelter type over the camp's life span.

Type of Shelter	Cost of a Single Shelter, USD	Durability	Occupancy Capacity (Members)	Number of Replacements over the Course of the Camp's Life Span	Total Cost per Single Shelter over a 15-Years Life Span, USD	Number of Shelters Needed/Year	Cost over a 15-Year Life Span, USD	Cost Efficiency
Tent	500	6 months	5	30	15,000	16,000	240 M	40%
Timber (pinewood)	27,429	5 years		3	82,288	10,000	823 M	83%
Steel	5232	3 years		5	26,160	10,000	262 M	45%
Prefabricated caravan	3125	3 years	6	5	15,630	13,500	211 M	32%
3D-printed	14,395	15 years	8	1	14,395	10,000	144 M	

The durability of the concrete shelters over the course of 15 years can be used to recover the value of the money spent on the purchase of a large number of printers to build the shelter camp. It will result in lower building costs than for other types of shelters when the cost of construction is spread out over the shelter's life span. The Al-Zaatari camp case study demonstrates an extremely effective and cost-saving construction methodology, which is superior to traditional construction methods for several types of shelters. The 3D printing technology is shown to be very competitive with respect to the basic types of shelters that require constant upgrades.

In addition, 3D-printed concrete shelters provide more safety from fire, improved structure durability, enhanced long-term stability, better energy efficiency, and thermal insulation. Furthermore, after refugees leave, printed shelters may be used to provide housing to low-income residents of the hosting countries, and the printable shelters could be sufficiently improved to be turned into resorts or stores.

6. Conclusions

The 3D concrete printing technology can be utilized to upgrade the Syrian refugee shelter design to provide new durable shelters with a long life span, better protection against extreme change in the desert climate, privacy, and cultural constraints. This article has proposed an AHP decision-making guide to apply this emerging methodology in construction by selecting the most appropriate technology among the major 3D printing methods: contour crafting, D-shape, and concrete printing. The proposed model considers the machine's technical characteristics, built structure characteristics, and economic and environmental aspects.

Contour crafting technology enables the construction of large-scale structures with the minimum waste of materials. Its ability to produce the maximum stable layer height, the ability to lay out utility conduits in the built structure, and the relatively moderate machine cost represent strengths among the three major methods. However, the relatively slow printing speed, higher maintenance cost, and fair mechanical properties of the built structure by this technology are challenges that must be addressed prior to the wide adoption of this technology in construction.

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