3D Printing: An opportunity for the sustainable development of building construction

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Abstract

Traditional construction processes have certain shortcomings, due to waste generation, as well as quality, safety and environmental problems, etc. In this regard, there are some technological innovations that represent an acceptable alternative to improve said construction processes in a specific country. One of them is 3D concrete printing (3DCP), which requires a printer consisting of a nozzle that extrudes and disposes layers of concrete following a previously-designed trajectory. Keeping that in mind, it is necessary to identify the main barriers that could prevent the successful implementation of this technology in a country to better target national policies and encourage the participation of the private sector. One way to achieve this is to present the main opportunities offered by this technology in the construction industry. In this research, we started with a literature review that allowed us to identify 6 opportunities and 10 barriers of 3D printing technology for whole houses. Then, a survey was designed to rate and score them through expert judgment, using the Analytical Hierarchy Process (AHP) method and its simplified version, Best Worst (BW), respectively. To validate this procedure, Peru was taken as an example, and 20 professionals from the construction industry with extensive professional experience were interviewed. It was thereby identified that the main opportunities are greater on-site safety, construction quality, and social benefits, while the main barriers to the implementation of full-size 3D printing are the technology under development, printing material, and the skills required for using this new technology.

Keywords –

3D-printed construction; 3D concrete printing; Technology adoption; Sustainability; Concrete

1 Introduction

Concrete is the main material used in the global construction industry and the second most used mixture in the global market. However, it is also a major contributor to greenhouse gas emissions [1], [2]. In building construction, the traditional construction processes with this material have many shortcomings, from the waste of resources [3], its high cost which makes it unaffordable [4], a high rate of occupational accidents [5], among others. In addition, there is a housing shortage in many countries, which is exacerbated by the steady global population growth [4].

Therefore, it is important to implement new technologies to overcome these problems and contribute to the sustainability of construction activities, being 3D concrete printing technology a great alternative which could be an important alternative [6]. This technology applies an automated process mainly based on the layered extrusion of concrete following a digital model, using a printhead or nozzle [7], [8].

Given that digital fabrication (DF) technologies have been being adopted in the construction industry in recent years, 3D concrete printing has become a focus of attention internationally due to the opportunities it offers, having begun to be implemented in some countries [9], [10]. These opportunities include, for example, greater freedom in architectural design, increased worker safety, time and cost savings, and reduced environmental impact [11], [12].

Although it presents different opportunities, in those countries where this technology has not yet begun to be investigated, let alone implemented, it is necessary to identify the main barriers that would exist for its optimal application. This evaluation of opportunities and barriers has already been carried out in other countries, based on a literature review, construction experts surveyed, and the identification of which opportunities and barriers would be the main ones to consider. In South Africa, its implementation was analyzed for low-cost sustainable housing, recognizing that the primary obstacle will be distributing the technology to the critical stakeholders of the construction sector[13]. In Europe, the main barriers are those related to stakeholder economic factors, technical and commercial factors, and traditional work culture [14]. In India, the main opportunity is their high speed of construction [15].

This research compiles the main opportunities and barriers for implementing full-scale 3D printing of concrete housing, which have been reported in recent research on this topic. Thus, those countries that wish to implement this technology and want to evaluate its potential main opportunities and barriers methodology that is based on experts' opinions and analyzes them applying the hierarchical method AHP (Analytical Hierarchy Process) and the simplified method BW (Best Worst). For this research, Peru was taken as an example of how this evaluation would be carried out.

2 Bibliographic review process

First, many scientific papers related to the topic were collected to identify the opportunities and barriers for the implementation of full-scale 3D concrete printing in construction projects. Papers were collected considering keywords to make sure that the paper was important for the carrying out of the research (see Table 1).

Table 1. Keywords and complements

	Keyword	Complement
1	3D concrete printing	Challenge
2	Additive Manufacturing	Barriers
3	Robotic 3D printing	Issues
4	3D printing	Opportunities
5	-	Problems
6	-	Enables

Then, a combination of keywords and complements was tried to find all possible options in the following databases: Scopus, ASCE, IEEE, Web of Science, and previous versions of ISARC. Thus, a total of 359 papers were retrieved. Then, we applied filters to ensure that the selected papers are aligned with our research objective. We excluded applied research and studies focused on specific topics, and instead prioritized papers that made a comprehensive list of opportunities or barriers related to the implementation of 3D concrete printing. Following these criteria, we narrowed down our initial list of papers to a final selection of 65 (see Figure 1). From them, the list of opportunities and barriers was obtained, these were grouped and are shown in sections 3 and 4.

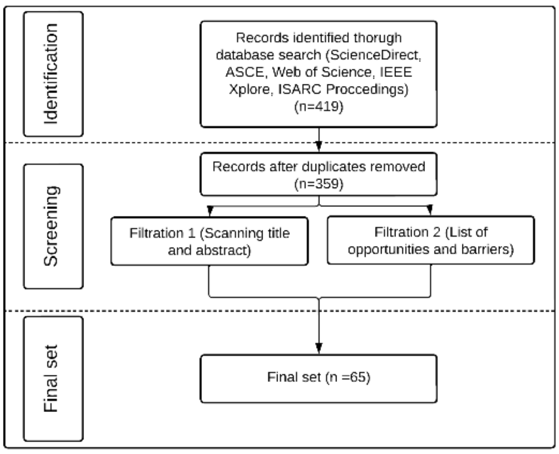

Figure 1. Bibliographic review flowchart

3 Opportunities of full-scale 3D concrete printing

The application of full-scale 3D concrete printing in the construction industry has multiple opportunities compared to conventional construction techniques. Based on the bibliographic study (see Table 2), we proceed to explain each of these opportunities.

3.1 Time saving and low cost

This includes, among others, the following:

- It generates a lower consumption of resources by not requiring formwork and steel reinforcement, and cancels any possible waste on site.
- Likewise, the geometry of the structure is optimized, requiring fewer materials (in volume) than in a traditional design. Approximately, construction time is reduced by up to 60% [48].
- In addition, the printing process is high-speed compared to traditional construction.
- Physical materials are also not required, thus eliminating the logistics associated with their purchase and placement on site.

3.2 Social benefits

This includes, among others, the following:

- It is ideal for the massive construction of affordable social housing, helping to reduce housing shortage in a country.
- It represents a market for the generation of new jobs.

3.3 Construction quality

This refers to the fact that, as the printing is automated, it improves the accuracy of the construction process, avoiding non-conforming products.

3.4 Freedom in architectural design

This includes, among others, the following:

- Complex architectural designs can be built without problems (such as curved walls), eliminating the design dependency of only replicated elements.
- It allows to generate eco-friendly designs, with better use of sunlight, ventilation, etc.

3.5 Increased safety at the construction site

Likewise, since printing is an automated process, the exposure of people to hazardous manual labor is reduced.

3.6 Environmental benefits during construction

This includes, among others, the following:

- It reduces energy footprint, carbon footprint and solid waste generation by requiring fewer resources and eliminating waste on site.
- It minimizes dust generation during construction work.

Table 2. Opportunities of 3D concrete printing

Item	Opportunities	Reference
O1	Time saving and low cost	[5], [10]–[13], [15], [17]–[40], [48]
O2	Social benefits	[4], [13], [17], [20], [21], [25], [30], [34]
O3	Construction quality	[12], [19]–[21], [24], [33], [41]
O4	Freedom in architectural design	[5], [7], [8], [10]–[12], [15], [17], [19]–[22], [24]–[27], [30], [33], [34], [37], [42], [43]
O5	Increased safety at the construction site	[10], [11], [13], [15], [17], [19]–[21], [23], [24], [27], [29]
O6	Environmental benefits	[7], [8], [11]–[13], [15], [17]–[25], [27]–[30], [33], [34], [41], [43], [44]

4 Barriers of full-scale 3D concrete printing

Similarly, the application of full-scale 3D printing in the construction industry has barriers that limit its successful implementation in a country. Based on the literature review (see Table 3), we proceed to explain each of these barriers.

Table 3. Barriers of 3D concrete printing

Item	Barriers	Reference
B1	Technology in development	[5], [8], [10], [12]–[15], [17], [19], [20], [22], [23], [26], [27], [29]–[32], [34]–[36], [39], [42]–[50]
B2	Printing material	[6], [12], [15], [19], [22], [23], [34], [43], [45], [46], [49]
B3	Social impact	[17], [22], [30], [44]
B4	Uncertainty about new technologies	[10], [30], [32], [35], [42], [43], [45]
B5	Environmental impact	[28]
B6	Cost of implementation and maintenance	[12]–[15], [17], [19], [44], [45]
B7	Dissemination of information	[10], [13]–[15], [17], [19], [34]
B8	Required capabilities	[5], [8], [10], [13]–[15], [17], [19], [29], [34], [51]
B9	Off-site manufacturing	[45]
B10	Operational failures	[12], [19], [30]

4.1 Technology in development

This barrier represents the following:

- There are no standards on mix design and quality testing for this type of concrete.
- There are no standards or software for its structural design, nor has the type of reinforcement it would include been defined (the mortar does not resist traction).
- There is a need to identify a wider variety of materials that can be used for printing.
- Its application is restricted to low-rise buildings.
- The project is limited to the dimensions of the terrain, the process required for printing, and the thickness and finish generated by the printed layers.

4.2 Printing material

This barrier represents the following:

- Cold joints caused between each layer of printed concrete, reducing its bonding strength.
- Printed material in a fresh state may deform.
- The print would suffer from cracking due to excessive shrinkage.
- The material would be sensitive to environmental conditions, especially extreme weather.

4.3 Social impact

Because the printer would perform most of the construction work, the demand for laborers would be decreased.

4.4 Uncertainty about new technologies

Being a new technology in the country, there is always uncertainty about its benefits and the risk of implementing it, despite foreign success stories.

4.5 Environmental impact

Printed buildings, being concrete-only, require greater use of cement, increasing carbon footprint.

4.6 Cost of implementation and maintenance

This barrier represents the following:

- There is a significant investment in the purchase of printers and the additional devices required, all of which are imported.
- Likewise, consider periodic maintenance for its proper operation.

4.7 Dissemination of information

This barrier represents the following:

- Low awareness of full-scale 3D concrete printing, its applications, and opportunities.
- It is not a subject that is taught in universities, nor are there local companies that provide training.

4.8 Required capabilities

This barrier represents the following:

- To have a professional who knows the technology, the optimal process to design the printing path, the cybersecurity of the equipment, its continuous monitoring, among others.
- Qualified technical personnel for the operation and maintenance of the equipment.
- To have suppliers that know the technology.

4.9 Off-site manufacturing

If 3D printing is used to manufacture components off-site, there will be an additional cost to transport them, and possible damage in transit.

4.10 Operational failures

This barrier represents the following:

- Nozzle clogging.
- Interruption in the flow of concrete, which could cause printing defects.

5 Survey design

After presenting the opportunities and barriers of this technology, if a country intends to implement it, then it should identify the order of importance of each of these to guide public policies and encourage private companies to invest in this technology.

First, it is necessary to validate the list of opportunities and barriers for a certain country to be studied. In this research, Peru was taken as an example case, to validate the procedure explained. The list of opportunities and barriers was validated by two experts in the Peruvian construction industry.

Then, to weight the importance of each one, the AHP and BW methods were chosen for the data analysis. The Analytical Hierarchy Process (AHP) is a decision-making method that involves multiple criteria and relies on expert pairwise comparisons, enabling the numerical quantification of the analyzed elements values . Unlike AHP, BW only compares references, which means that it only needs to determine the preference of the best criterion over all other criteria and the preference of all criteria over the worst criterion using a number between 1 and 9 [F, G].

5.1 Opportunities

After the literature review, 6 general opportunities were obtained in the implementation of full-scale 3D printing, which is why we chose to use the AHP method, which is a multi-criteria decision-making process based on pairwise comparisons made by experts, which in turn allows numerically measure the values of the elements analyzed [16], [52]. The survey asked 15 questions comparing opportunities based on established criteria (see Table 4).

Table 4. Importance criteria

Scale	Name	Description
1	Equal importance	Both alternatives are of equal importance.
3	Slight importance	One of the alternatives is slightly more favored.
5	Moderate importance	One of the alternatives is favored moderately more.
7	Strong importance	One of the alternatives is strongly favored.
9	Completely more important	One of the alternatives is strongly favored.

5.2 Barriers

In the case of barriers, the BW method was used, which is used to calculate the weights of criteria and alternatives based on pairwise comparisons with the least amount of data. Compared to other methods, fewer pairwise comparisons are made from which criteria weights are obtained [53], [54]. Unlike AHP used in opportunities, BW only compares benchmarks, which means that it only needs to determine the preference of the most important barrier over the rest of the barriers and the preference of all barriers over the least important barrier following the criteria already established (see Table 4). In this research, 18 questions were asked using the Best Worst method.

6 Data analysis

In total, 20 professionals with experience in the Peruvian construction industry were surveyed, asking them about their personal data and questions related to opportunities and barriers.

6.1 General data

Each respondent was asked about his or her academic degree and the following results were obtained (see Table 5).

Table 5. Academic degree

Academic degree	Percentage concerning total respondents
Graduate Engineer	90%
Magister	65%
Doctor	10%

Next, respondents were asked about their profession (see Table 6).

Table 6. Profession

Profession	Percentage concerning total respondents
Civil Engineer	85%
Architect	5%
Others	10%

In addition, each respondent was asked about his or her current job (see Table 7). Many had more than one job at the same time

Table 7. Current job

Work currently performed	Percentage concerning total respondents
Construction company	30%
Supervision	30%
Designer	5%
Supplier	0%
Consultant	35%
Laboratory	15%
Public Management	10%
Teaching	55%
Research	45%

The last question of the general data was about their professional experience, where the following results were obtained (see Table 8). Many had more than one type of experience.

Table 8. Professional experience

Professional experience type	1 to 5 years	6 to 10 years	More than 10 years
University teaching in courses related to construction processes and/or concrete technology.	15%	5%	30%
Construction of civil works in general, including supervisory and/or consulting work.	25%	25%	40%
Related to concrete technology: Research, materials laboratory and/or supplier.	15%	10%	20%

6.2 Qualification results

The AHP method was used for opportunities, where 15 questions were asked comparing them in pairs. In the case of barriers, the Best Worst method was used, obtaining 18 questions. Tables 9 and 10 present the results of the surveys, with the qualification obtained by each one.

Table 9. Qualification of opportunities

Item	Opportunity	Average rating	Ranking
O1	Time saving and low cost	0.186	4°
O2	Social benefits	0.190	3°
O3	Construction quality	0.208	2°
O4	Freedom in architectural design	0.061	6°
O5	Increased safety at the construction site	0.227	1°
O6	Environmental benefits	0.129	5°

Table 10. Qualification of barriers

Item	Barrier	Average rating	Ranking
B1	Technology in development	0.170	1°
B2	Printing material	0.113	2°
B3	Social impact	0.092	6°
B4	Uncertainty about	0.109	4°

	new technologies		
B5	Environmental impact	0.079	8°
B6	Cost of implementation and maintenance	0.100	5°
B7	Dissemination of information	0.072	10°
B8	Required capabilities	0.110	3°
B9	Off-site manufacturing	0.081	7°
B10	Operational failures	0.074	9°

7 Conclusions

After having evaluated 65 scientific papers related to the implementation of full-scale 3D printing technology for housing, 10 barriers that would limit its implementation in a country have been identified, as well as 6 opportunities for its successful implementation.

A survey based on the AHP method was designed to rank the barriers and advantages according to the opinions of experts in each country. Taking Peru as a case study, 20 professionals with experience in the Peruvian construction industry were surveyed, who have many years of experience related to university teaching in construction, construction projects and concrete technology.

The main opportunities for the implementation of full-scale 3D printing of houses in Peru were the increased safety at the construction site (22.7%), construction quality (20.8%), and social benefits (19%). This reflects the great benefits that this technology will have on national development, from the point of view of experts, which should reinforce state and private support.

The main barriers were technology in development (17%), printing material (11.3%), and required capabilities (11%). With this result, the country will be able to guide improvement actions to overcome these barriers.

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