Critical Success Factors for Implementing 3D Printing Technology in Construction Projects: Academics and Construction Practitioners' Perspectives

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Abstract

Purpose – The application of 3D printing technology in construction projects is of increasing interest to researchers and construction practitioners. Although the application of 3D printing technology at various stages of project lifecycle has been explored, few studies have identified the relative importance of critical success factors (CSFs) for implementing 3D printing technology in construction projects. To address this research gap, this study aims to explore the academics (i.e., researchers) and construction practitioners' perspectives on CSFs for implementing 3D printing technology in construction projects.

Design/methodology/approach – To do this, a questionnaire was administered to participants (i.e., academics and construction practitioners) with knowledge and expertise in 3D printing technology in construction projects. The collected data were analyzed using mean score ranking, normalization, and rank agreement analysis to identify CSFs and determine the consistency of the ranking of CSFs between academics and construction practitioners. In addition, exploratory factor analysis was used to identify the relationships and underlying constructs of the measured CSFs.

Findings – Through a rank agreement analysis of the collected data, eleven (11) CSFs for implementing 3D printing technology were retrieved (i.e., 17% agreement), indicating a diverse agreement in the ranking of the CSFs between academics and construction practitioners. In addition, the results show three key components of CSFs including "production demand enabling CSFs", "optimize the construction process enabling CSFs" and "optimized design enabling CSFs".

Originality – This study highlights the feasibility of implementing the identified CSFs for 3D printing technology in construction projects, which not only severs as a reference for other researchers, but also increases construction practitioners' awareness of the practical benefits of implementing 3D printing technology in construction projects. Specifically, it would optimize the construction lifecycle processes, enhance digital transformation, and promote sustainable construction projects.

Keywords: 3D printing technology; Construction projects; Critical success factors (CSFs); Factor analysis; Rank agreement analysis; Questionnaire.

Paper type: Research paper

Introduction

The construction industry is one of the most prominent industries in the world because of its contribution to economic growth, job creation, sustainable infrastructure, and among others (El-Sayegh et al., 2020; Opoku et al., 2021). According to the World Bank (2015a), the construction industry accounts for about 6% of global gross domestic product (GDP), with total annual revenues of almost $ 10 trillion and added value of $ 3.6 trillion. However, the construction industry has also been recognized as experiencing a low productivity rate, consuming a considerable number of resources, and producing significant environmental issues (Lowke et al., 2018; Wu et al., 2016). For example, traditional building construction leads to the destruction of non-renewable natural resources and increases the burden on the environment. Greenhouse gases are generated during waste disposal, transportation, and manufacturing of construction materials (Drager & Letmathe, 2022; Xu et al., 2020). Consequently, the construction industry must improve its performance (Kreiger et al., 2015) to meet population growth (Asif, 2016), and to solve problems such as high energy consumption, low material utilization, and high waste generation rates in traditional construction projects (Alohan & Oyetunji, 2021).

Ghaffarianhoseini et al. (2017) suggested that the adoption of digital technologies could provide an opportunity for the transformation of traditional architecture, engineering, and construction (AEC) sector. 3D printing technology, as one of the digital technologies, is considered as an important driver of digital transformation in the construction industry (El-Sayegh et al., 2020). Bogue (2013) pointed out that 3D printing is a technology for creating 3D solid items from a digital model that is mechanized and additively manufactured. Researchers have a relatively consistent description of the functions and characteristics of 3D printing technology. It is considered as an environmental friendly derivative (Hager et al., 2016), with a potential stimulus for sustainable development (Gebler et al., 2014). Zhang et al. (2019) stated that using 3D printing technology can save 50 to 80% of labor costs, 50 to 70% of production time, and 30 to 60% of construction waste.

Presently, 3D printing technology has already achieved numerous practical applications in the aerospace, medical, manufacturing, and food industries (Martinez et al., 2022; Sandeep et al., 2021; Sun et al., 2015; Yan et al., 2018). However, the practical application of 3D printing in construction projects is still very rare with few real-world applications such as the footbridge project undertaken by the Institute of Advanced Architecture Catalonia (IAAC) (Anjum et al., 2017; IAAC, 2016), a multi-storey flat built by the Eindhoven University of Technology in the Netherlands, and an office building in Dubai (Zhang et al., 2019). Therefore, advancing the practical application of 3D printing technology in construction projects and breaking through traditional construction processes remain an urgent goal. As such, an in-depth exploration of the effective interventions or critical success factors (CSFs) for implementing 3D printing technology in construction projects could improve stakeholders' awareness, thus, enhancing digital transformation in the industry.

Given the extant literature on 3D printing technology (Buchanan & Gardner, 2019; Pan et al., 2021; Tay et al., 2017), there is still a knowledge gap in identifying the CSFs for implementing 3D printing technology in construction projects. According to Chan et al. (2010), CSFs are few key areas of activity where managers need favorable outcomes to reach their goals. As such, CSFs represent those effective interventions that must be given a high level of attention during the life cycle of a construction project.

Given the above, this study aims to explore the academics (i.e., researchers) and construction practitioners' perspectives on CSFs for implementing 3D printing technology in construction projects. To achieve the stated aim, a questionnaire was used for data collection and administered to participants (i.e., academics and construction practitioners) with knowledge and expertise in 3D printing technology in construction projects. The findings would provide effective interventions that could be used as key recommendations for researchers and practitioners to promote 3D printing technology. This study contributes to digitalization of the construction industry by enabling construction practitioners to understand the potential benefits of 3D printing technology. In addition, the results of this study would establish the relationship between advanced digital technology and construction project success criteria for future research.

Literature review

Success factors for implementing 3D printing technology in construction projects

Many researchers have proposed several success factors for implementing 3D printing technology in construction. El-Sayegh et al. (2020) pointed out that the interventions of 3D printing technology in construction are mainly due to its constructability and sustainability in relation to the environment, cost, stakeholders, and management. It has been demonstrated that 3D printing technology contributes to economic, environmental, and construction returns, showing a positive trend towards digital transformation (Guimaraes et al., 2021). Additive manufacturing and rapid manufacturing technologies help to produce parts/components of an object for rapid prototyping, which *makes it easy to develop a model or prototype* (Buswell et al., 2007). 3D printers are used to produce components (Buswell et al., 2007), which aid in developing prototypes more quickly throughout all stages of production.

The root cause of additive manufacturing is the elimination of the reliance on tools in traditional manufacturing processes, thereby *reducing the overall project time* (Buswell et al., 2007). According to Guimaraes et al. (2021), 3D printing technology can reduce the construction time of masonry structures by 35%. 3D printing technology has been used in free-form architectural design and model prototyping for many years, and it is currently evolving as a prototyping tool in manufacturing (Gohn et al., 2022). 3D printing technology enhances *mass customization of building components* and *increases freedom of design for complex buildings* (De Schutter et al., 2018). *Injection molding* is often used to produce large amounts of parts/components. 3D printing technology can be combined with injection molding to reduce the lead time for mold manufacturing (Dizon et al., 2019). The use of 3D printing technology in construction projects mostly focuses on producing concrete elements, with the involvement of digital modelling software to *visualize part geometry of the components* (Sangiorgio et al., 2022), giving the production process the ability to create complex geometries (Godoi et al., 2016).

The digital manufacturing process uses structural optimization and functional hybridization as basic design ideas, *increasing the complexity of the shape* (De Schutter et al., 2018). Since building information modeling (BIM) has the ability to visualize and interact with data, component and material information can be circulated among stakeholders for timely *communication about product characteristics and types* (He et al., 2021). 3D printing technology is a computer-controlled manufacturing method that can *increase the flexibility of the manufacturing process***.** The combination of BIM models and 3D printing technology can *provide mass properties of the product* during the 3D printing process, as well as facilitating open communication between stakeholders, providing more diverse manufacturing plans, and *setting milestones* to make the *manufacturing process more flexible* and more responsive to consumer needs (Beltagui et al., 2020; He et al., 2021).

BIM technology has been shown to facilitate the development of 3D printing technology as a way of modelling building information. BIM can share information and knowledge about 3D buildings and form a reliable source of decision making during the whole life cycle of a project, with *client's needs and assessments being communicated to project team* (Shahrubudin et al., 2019). Dadi et al. (2014) argued that the adoption of paper documents and drawings for engineering information delivery is a source of inefficiency in communication and design. Computer-aided design in 3D printing *reduces the use of paper documents* and the project team can use BIM techniques to visualize designs, which make 3D models efficient due to 2D drawings. In addition, the integration of 3D printing technology and BIM can *enhance design coordination*. By analyzing data from all phases of the project, the project team can improve design quality and efficiency, and also *identify errors in the* *early stages of design* (Han et al., 2012). In the design and production stages of 3D printing, the product can be 3D scanned and parameterized through computer assistance, whilst the prototype design can be carried out according to customer's requirements using automated technology. This is *convenient for form, fit, and function testing* (Greder et al., 2020). Printed prototypes can be considered as final products for form, fit, and function testing, thereby reducing the cost of repetitive experiments.

In addition to its advantages on a technical level, 3D printing technology can also bring economic and social benefits. From the perspective of traditional construction approaches, the construction industry is a labor-intensive industry and encounters many occupational injuries (e.g., musculoskeletal disorders, fall from same levels, physical fatigue, etc) (Kisi et al., 2017; Anwer et al., 2021). All stages of traditional construction lifecycle require huge human resource input, tools/equipment, and materials which increase construction waste. In contrast, 3D printing technology, as an advanced digital technology, requires digital modeling software, thus, fewer tools/equipment, human input, and materials are needed in the design and production stages. Consequently, the manual process that requires a lot of *labor inputs and material wastes are greatly reduced* (Hossain et al., 2020). 3D printing technology can accurately measure the amount of building materials, hence, the saturated use of building materials can effectively *reduce the total project cost* (Guimaraes et al., 2021). According to Allouzi et al. (2020), 3D printing technology can reduce material costs by 65%. In traditional construction approaches, formwork accounts for about 25 to 30% of the project cost (Mechtcherine et al., 2019). Since 3D printing technology can reduce the use of production molds and the employment cost of construction personnel, it can *significantly reduce project cost* (Hossain et al., 2020).

It has been demonstrated that 3D printing technology *enhances occupational health and safety* (Zhang & Mohandes, 2020). For instance, 3D printing technology improves resource efficiency and reduces the retention of toxic substances as compared to traditional construction approaches. In addition, the emergence of 3D printing technology has simultaneously facilitated the development of new materials and reduced the frequency of contact with toxic materials (Ning et al., 2021). Buchanan and Gardner (2019) stated that increased automation during the construction phase can lead to safer and more accurate completion of tasks on site. The durability of 3D printed structures is a key step to better address sustainability challenges (Lafhaj & Dakhli, 2019). The durability of a building depends on design accuracy, material characteristics, and environmental conditions. 3D printing technology can *increase the durability of a building* by completing complex internal designs through information modelling techniques, and integrating analysis of the external environment and design characteristics (Grassi et al., 2019). 3D printing integrated web environment enables the construction of a sustainable model that can describe green production processes whilst enhancing optimal work assignments and dealing with data uncertainty (Ma, 2020). Therefore, it is opined that a management model based on 3D printing technology can lead to *clarification of construction projects*.

Research methodology

Identification of CSFs for implementing 3D printing technology

To identify the CSFs for implementing 3D printing technology, a comprehensive review of relevant literature on "success factors", "critical success factors", "3D printing technology" and "construction projects" was conducted to critically appraise and synthesize the findings of previous studies (i.e., journal articles, conference papers, etc.) in this domain. A list of 20 potential success factors for implementing 3D printing technology in construction projects was initially established. A pilot study was conducted to seek the opinion of selected academics and construction practitioners on the potential success factors of 3D printing technology. The purpose of this pilot study was to test the significance and comprehensiveness of the success factors (Adabre & Chan, 2019; Li et al., 2011). No additional success factor was proposed by the selected participants during the pilot study. From the methodological perspective, the questionnaire was used for data collection because of the flexibility in survey time and it is relatively manageable (Aksu, 2009). In addition, questionnaire is often used for data collection in situations such as cross-regional, busy respondents and anonymous surveys (Roopa & Menta Satya, 2012). Considering the uncertainty of respondents' availability, this study mainly used questionnaire to solicit responses from academics and construction practitioners in order to achieve the key CSFs for implementing 3D printing technology in construction projects. Therefore, academics and construction practitioners with industrial experience in the studied domain were required to respond to the questions in the questionnaire. The 20 success factors for implementing 3D printing technology and related sources are listed in Table 1.

[Please insert Table 1 about here]

Data collection

A questionnaire was mainly used for data collection. It consists of 20 success factors for implementing 3D printing technology that were initially appraised and synthesized from a comprehensive literature review. Our goal was to identify the key CSFs among the 20 success factors, conduct an agreement analysis between respondents (i.e., academics and construction practitioners) on the ranking of the CSFs, and categorize the underlying constructs of the measured CSFs.

The questionnaire is mainly divided into two parts, section A and section B. Section A mainly asks for the basic information of the respondents, including their gender, age, and position. It was intended to solicit the respondents' demographics and whether they have sufficient knowledge about the construction industry to respond to the questionnaires that meet our objectives. On the other hand, section B contains two questions. The first set of questions in section B was to solicit responses on the success factors of 3D printing technology. The second part in section B focuses on the application fields of 3D printing technology. The questionnaire requested the respondents' attention to these application fields, judged the current development status of 3D printing technology, determined whether the application of this technology in the construction industry is valued, and the necessity of studying the application of this technology in the construction industry. Overall, the questionnaire involved respondents' demographics, 20 success factors, and application fields of 3D printing technology, where respondents were asked to evaluate the relative importance of each success factor to determine the most effective interventions and practical applications.

The questions in section B are presented in the form of Likert scales, which seek to quantify the collected data. Using a 5-point scoring standard, respondents' subjective opinions were converted into numerical values that can be quantitatively analyzed and visually presented in charts. A Likert scale of 1 to 5 is the scoring standard set used in this research. This scale is relatively more concise, of which 5 is very important; 4 is important; 3 is neutral; 2 is less important; 1 is not important. The questionnaire was designed to seek responses from potential respondents of the importance of studying the success factors of 3D printing technology, and then based on their expertise they can appropriately rate the critical degree of factors driving the development of 3D printing technology in construction projects. To ensure the authenticity and validity of the survey, it should be noted that sufficient samples were retrieved, and the responses from non-construction practitioners were filtered out to ensure the objectivity and reliability of the results.

Figure 1 depicts an overview of the research framework. The survey was fully launched in February 2022. During the research process (see Figure 1), the questionnaires were administered to architectural design companies, real estate companies, cost architect firms, etc., such as Building Design Partnership (BDP), Arup, many of which are multinational companies. These companies have extensive experience in project design, operation, construction, and maintenance. The respondents also included architects, project managers, technicians, cost engineers, engineers, and academics. They have extensive research or work experience on "3D printing technology in the construction industry", and a wealth of other construction-related digital innovation knowledge. Basic information about companies, academics, and construction practitioners, including their names, email addresses, projects undertaken (i.e., experience in the field), etc. were obtained from academic outputs (e.g., journals, conference papers), membership lists of professional associations, company websites, social media platforms (e.g., LinkedIn).

[Please insert Figure 1 about here]

Overall, 73 questionnaires were administered to academics and construction practitioners in construction companies. A link to the questionnaire was sent to the potential respondents by email. The questionnaires were created through the "wenjuanxing (WJX)" and survey monkey platforms. For those companies that did not have access to email addresses, the questionnaire was uploaded to the message section of the company's website and respondents were given approximately 4 weeks to complete the questionnaire, with responses displayed directly on the backend of WJX and survey monkey. These options of questionnaire administration were employed to enhance the response rate (Adabre & Chan, 2019).

Of the 73 questionnaires that were administered, 31 were retrieved, 25 were valid and 6 were invalid. As such, 25 questionnaires were used for analyses, and the response rate was 34.25%. It has been reported that over 25% of the valid response rate to the questionnaire was considered feasible (Idrus & Newman, 2002). Therefore, it is considered that the sample size of this study is sufficient to support the follow-up analyses.

Respondents' profile

To make the research results more practical, generalized, and represent the actual situation as much as possible, the questionnaires were randomly distributed to well-known companies, academics, and construction practitioners. Considering the heavy workload of experts and the difficulty in soliciting opinions (Adabre & Chan, 2019), this study received and analyzed 25 valid questionnaires. Figure 2 illustrates the position distribution of respondents. The target samples include 1 technician (4%), 1 project manager (4%), 6 boffins (24%), 4 quantity surveyors (16%), 7 engineers/architects (28%), and 6 academics (24%), as shown in Figure 2. Figure 3 presents the gender distribution of respondents. Among the 25 complete and valid responses, as shown in Figure 3, 16 were males (64%) and 9 were females (36%). It can be seen that there are slightly more male respondents than females in this study. Figure 4 shows the age distribution of respondents. The histogram clearly identifies age clusters in valid responses. It was found that 23 respondents were under the age of 50, accounting for 92% of all valid samples, whilst only 2 respondents were over 50 years old, accounting for 8% of the overall valid samples, as shown in Figure 4. The respondents' profiles illustrate that the data collected from these respondents help study the opinions of construction professionals in different positions and companies of different scopes on 3D printing technology, making the results more generalized.

[Please insert Figures 2, 3, and 4 about here]

Analyses and results

To determine the key CSFs for implementing 3D printing technology in construction projects, this study used normalization, rank agreement analysis, and exploratory factor analysis. First, the mean and standard deviation were calculated for each group, and their normalized values were estimated to determine the criticality of each factor (i.e., success factor). Normalization is the process of organizing a database to reduce redundancy and improve data integrity. Normalization generally refers to processes that achieve scales between 0 and 1. A success factor was defined as critical when the normalized value was ≥ 0.50 (Adabre & Chan, 2019; Osei-Kyei & Chan, 2017). In addition, this study used agreement analysis from both academic and construction practitioners to judge the degree of acceptance of the rankings of the identified CSFs for implementing 3D printing technology. Finally, the Statistical Package for Social Sciences (SPSS) version 17.0 software was used to conduct an exploratory factor analysis of the CSFs to identify their relationships and underlying constructs. The results of the analyses and discussion are further expanded below.

Mean score ranking and normalization

Table 2 presents the ranking of CSFs for implementing 3D printing technology in construction projects. We sorted the data from 25 valid questionnaires and calculated the mean, standard deviation, and normalization values, as shown in Table 2. Among them, the mean value of "improved ability to visualize part geometry" (SF05) was 4.20, with a standard deviation value of 0.816, ranking first. The "increased durability of buildings" (SF16) factor was ranked last with a standard deviation value of 1.291 and a mean value of only 3.00. Normalization takes 0.5 as a reference value, and when normalization values were ≥ 0.50, the identified success factor is considered critical (i.e., effective intervention). According to the calculated normalization values, 11 CSFs were identified, as shown in Table 2. Among the identified CSFs, "improved ability to visualize part geometry" (SF05), "make it easy to develop a model or prototype" (SF19), "increase the design freedom of complex building" (SF02), "earlier detection and reduction of design errors" (SF06) and "convenient for Form, fit and function testing" (SF11) are the five most important CSFs.

[Please insert Table 2 about here]

Rank agreement analysis

In this study, the rating data were collected from experienced respondents to calculate the mean and normalized values of each group of data. As shown in Table 2, eleven (11) success factors were identified as CSFs. It is worth noting that the respondents were divided into two groups (i.e., academics and practitioners) due to their different expertise and knowledge on the development and successful application of 3D printing technology. Since only 25 sets of valid data were collected and the sample size was limited, parametric analysis could not be used to determine whether there was a significant difference between the two groups. Consequently, it could not be determined whether the two groups agreed on the rankings of the 11 CSFs. To determine the agreement among academics and construction practitioners on the CSFs for 3D printing technology, this study employed a sequential rank agreement measure to quantify the rank agreement among two or more ordered lists (Ekstrøm *et al.,* 2019) and proposed the "rank agreement factor" (RAF) (Adabre & Chan, 2019) to further calculate the percentage agreement of the two groups of data. For any two groups, it is assumed that the rank of the *i*-th item in group 1 is R_{i1}, and the rank of the *i*-th item in group 2 is R_{i2}. In this study, academics were classified as group 1, whilst construction practitioners constituted group 2. N is the number of items, i.e., 11 CSFs. K is the number of respondents from both parties. Before further analysis, an hypothesis was proposed that:

H0：There is no good agreement in the ranking of the 11 CSFs between academics and construction practitioners.

The absolute difference Di of the i-th item of the two groups is

$$D_i = |R_{i1} - R_{i2}| \quad (1)$$

Where $\mathrm{i} = 1, 2, \ldots, \mathrm{N}$ and $\mathrm{N} = 11$

$$R_i = \sum_{i=1}^{N} (R_{ij}) \quad (2)$$

Where Rij is the sum of the ranks given to a particular CSF by the two different groups.

The mean of the total ranks (Rj2) is:

$$R_{j2} = \frac{R_i}{N} \quad (\mathrm{j = N - i + 1}) \quad (3)$$

The rank agreement factor (RAF) is:

$$\mathrm{RAF} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} D_i}{\mathrm{N}} \tag{4}$$

While the RAF_{max} is:

$$RAF_{max} = \frac{1}{\mathrm{N}}\left(\sum_{\mathrm{i}=1}^{\mathrm{N}} \left|\mathrm{R}_{\mathrm{i}1} - \mathrm{R}_{\mathrm{j}2}\right|\right) \tag{5}$$

The percentage disagreement (PD) and percentage agreement (PA) are:

$$\mathrm{PD}(\%) = \frac{\mathrm{RAF}}{RAF_{max}} \mathrm{x}\, 100 \tag{6}$$

$$\mathrm{PA}(\%) = 100 - \mathrm{PD} \tag{7}$$

The rank agreement analysis has been applied in previous studies (Choudhry et al. 2012; Adabre and Chan 2019). Choudhry *et al.* (2012) showed that the RAF can be greater than 1, and the lower the RAF value, the higher the level of consistency between the two groups. When the RAF is 0, the two groups of data can be considered to be in complete agreement. By substituting the research data into equations (1) to (7), the results are shown in Table 3. From the analyzed data, it can be calculated that PD = 0.829 = 83%, PA = 100-PD, so PA = 17%. This indicates that the percentage of agreement for 11 CSFs is only 17%. Therefore, it was revealed that both academics and construction practitioners have different opinions on the 11 CSFs, and the null hypothesis holds.

[Please insert Table 3 about here]

Further analysis of the results shows that academic respondents evaluated 3D printing technology application from both theoretical and practical perspectives to ensure its implementation in construction projects. As shown in Table 3, academic respondents ranked both “increase the design freedom of complex building” (SF02) and “improved ability to visualize part geometry" (SF05) as the key CSFs for implementing 3D printing technology. It is reported that scholars are more focused on breakthroughs in the materials required for 3D printing (Ulm, 2012). Innovations in concrete materials offer new degrees of freedom in the design and construction of concrete infrastructure. Special concrete materials that have been molecularly and nano-modified may become essential for 3D printing, reducing the ecological processes of materials, and promoting concrete sustainability while meeting the design ecology, functionality, and safety of buildings. The development of 3D printers is the driving force behind the introduction of 3D printing technology into construction projects. Lang et al. (2020) reported that 3D printing can use virtual images generated by software to design component shapes, and printer nozzle can use a wide range of parametric degrees of freedom to adapt to the component to be produced. Optimizing printing methods and shapes according to design goals, helping customers and suppliers to choose the best design in a short time and reducing waste are iterative processes (Biswas et al., 2019).

Construction practitioners paid more attention to the practical application of 3D printing technology in real-world engineering projects, thus focusing on how mistakes or wastes in prototype iterations can be reduced in the early stage. They claimed that “make it easy to develop a model or prototype” (SF19) and “improved ability to visualize part geometry" (SF05) were the most important CSFs for architectural visualization and development (see Table 3). Construction practitioners (e.g., engineers) can create visual designs as digital objects that can be realized as tangible building models through 3D printers to generate real or physical buildings (Fittkau et al., 2015). Visualization tools can enhance communication between project teams, improve integration during the design phase, provide accurate building information to design and build teams, and have the ability to achieve high-performance design goals for buildings (Korkmaz et al., 2010). In the process of prototyping, 3D printing can choose different printing methods according to different materials, which is flexible and can maintain the utility of parts, reducing the compensation waste for durability and quality (Sathish et al., 2018). “Make it easy to develop models or prototypes” (SF19) and “improved ability to visualize part geometry" (SF05) had become the foundation for practical application of 3D printing in manufacturing, and they have the potential to drive the use of 3D printing in the construction industry.

The diverse perspectives from academics and construction practitioners on implementing 3D printing technology may lead to their disagreement on the ranking of the 11 CSFs. Although some CSFs were ranked in similar viewpoints, the overall level of agreement was low. Academic respondents often discussed how green and efficient innovations can be targeted at 3D printing (Ning et al., 2021) to develop practical technologies that better meet the needs of the industry. Conversely, construction practitioners were more interested in how 3D printing technology could alleviate the stress of workers at all stages of project lifecycle to achieve sustainability in construction projects. Notably, sustainable development and efficiency are in line with the overall trend of modern methods of construction, thereby increasing the recognition of 3D printing technology in the construction industry and contributing to the success of its application in construction projects.

In addition, the requirements of sustainable development would stimulate researchers’ enthusiasm for research and development in 3D printing technology. Therefore, promoting sustainable development and technological innovation can benefit various stakeholders of the AEC sector. Construction industry accounts for a large proportion of the national economy and provides numerous job opportunities for society. The emergence of 3D printing technology could replace several operating procedures and manual tasks, resulting in a decline in labor demand. Further innovation of 3D printing technology in the construction industry requires workers to have professional knowledge and continuous learning to improve their daily workplace activities (Ning et al., 2021). In addition, 3D printing technology has a potential breakthrough in the architectural design stage. Digital fabrication is an attempt to make 3D printing technology a reality in construction projects. This technology can be used in conjunction with other modeling software. For example, the combination of 3D printing technology and BIM can automatically design a printing path after obtaining digital information through BIM. This integration can provide support for architectural design, 3D displays of design models, and mitigate design defects. Practical applications in foundation design have great potential to overcome traditional architectural problems (Ning et al., 2021). However, from the perspective of sustainable application, 3D printing technology still faces many challenges such as legislation, cost, and real-world application process. So far, the application of 3D printing technology is still at the preliminary conceptual stage, without standardized processes and paradigms (Buchanan & Gardner, 2019), and with limited monitoring conditions and institutions (Zhao et al., 2020). As such, it is difficult to control product quality and further standardization is required. Moreover, construction projects are generally complicated and involve many stakeholders in real-world application. Therefore, it is necessary to develop data management platforms to solve problems such as information transfer and coordination among stakeholders.

Factor analysis of the CSFs

As previously mentioned, this study used 25 valid samples to conduct an exploratory factor analysis of 11 CSFs for implementing 3D printing technology in construction projects. Although it constitutes a small sample size, de Winter et al. (2009) showed that exploratory factor analysis can still produce high quality results when the factor loadings are large, even for a small sample size. The factor loadings are presented in Table 4. As shown in Table 4, the factor loadings were above 0.7. According to Hair et al. (1995), factor loadings are considered to be low and high when they are below 0.4 and greater than 0.6, respectively. Therefore, it can be concluded that the 25 valid samples used in this study met the requirement for exploratory factor analysis for 11 CSFs.

[Please insert Table 4 about here]

Internal reliability

Cronbach's alpha (α) is the most common measure of internal reliability. The internal reliability of the 11 CSFs in this paper can be evaluated by using the α coefficient. The resulting α coefficient of reliability ranges from 0 to 1, with higher α values indicating higher internal consistency for a range of factors in the list (Santos, 1999). By using SPSS software for reliability analysis, α was 0.922. The α value indicates that the 11 CSFs are internally consistent with each other. Factor analysis is a method to process data dimensionality reduction. In practical application, it mainly seeks a few independent common factors of multiple indicators to explain the relationship between original indicators and individual feature descriptions (Fan & Feng, 2013; Shrestha, 2021; Taherdoost et al., 2022). Since this study obtained 11 CSFs, exploratory factor analysis was adopted to identify the relationships and underlying constructs of a small set of measured CSFs that could be useful for construction stakeholders in implementing 3D printing technology in construction projects.

Since the variable score adopts a 5-point Likert scale, there is no need to standardize the variables, and the construct validity analysis can be carried out directly. The correlation test of 11 CSFs was carried out by Kaiser Meyer Olkin (KMO) and Bartlett's test of sphericity before further analysis, so as to verify whether this group of data can be analyzed (Bernard & Munasinghe, 2020). The KMO value for this study data was 0.596, which was above the limit of 0.5. The result of Bartlett test is 210.719, and the significance level is 0.00, which is much smaller than the significance level value of 0.05. These results show that the correlation matrix of this group of data is a positive matrix with significant correlation, which is suitable for factor analysis. In the research process, it is necessary to first use the principal component analysis method to extract factors and simplify the variables into comprehensive variables. Eigenvalue is an indicator to measure the contribution of principal components. In this study, only variables with eigenvalues greater than or about 1 were retained (Adabre & Chan, 2019; Chan *et al.,* 2018). As a result, all the 11 CSFs were retained. By using varimax rotation to extract three underlying components, the cumulative variance was 78.903%, indicating that the three extracted components together explain 78.903% of the total variance of the 11 CSFs. Furthermore, since variables with factor loadings higher than 0.50 are defined as significant, this study only used variables with factor loadings over 0.50, as shown in Table 5. It is worth noting that there may be a case in which one factor corresponds to two components in the component matrix, indicating that the element has a high load on both factors.

[Please insert Table 5 about here]

Discussion

Component 1: Production demand enabling CSFs

Component 1 includes 5 CSFs, namely "improved ability to visualize part geometry", "make it easy to develop a model or prototype", "convenient for form, fit, and function testing", "more flexible manufacturing process", and "tooling for injection molding". These CSFs are closely related to improving sustainable production of components. Therefore, this component was named as "production demand enabling CSFs". The variance of this component is 28.983% as shown in Table 5.

This component is determined by the technical characteristics of 3D printing technology. 3D printing's dependence on digital systems and printer performance is a major concern for academics and construction practitioners. 3D printing is considered as a technology that can create a green production process, and the most effective way to integrate this technology is to complement it with other resources rather than changing the entire production process (Besklubova *et al.,* 2021). This plausible way of implementing 3D printing technology to the production line of building components can improve the traditional process. Cai *et al.* (2019) found that 3D printing technology can support energy saving and emission reduction through software, hardware development, and incentives to perform new process operations. These improvements increase the conversion rate of materials by reducing errors and repetitive operations during the production process, enabling sustainable production of components. 3D printing technology is therefore compatible with the potential values of green production. Researchers and practitioners have proposed various innovations and applications of this technology in the processing phase to convince stakeholders of the need for 3D printing technology. Some of these testing issues for finished products can be solved by refining 3D printing technology. The production of building products through 3D printers requires rigorous quality monitoring in the early and late stages. A qualified 3D printed building product requires form, fit, and function testing. Reedy (2022) explained that "form-fit-function (FFF)" is used in manufacturing to describe the identifying characteristics of a part/component. "Form" involves the shape, size, dimension, mass, weight, and other visual parameters that uniquely distinguish them from one another. "Fit" is the ability of a part to physically interface with, connect to, or become an integral part of another part. "Function" is the action that a part is designed to perform." Form, fit and function testing can help architectural firms to produce attractive and accurate prototypes that function almost indistinguishable from the final product. Alternatively, a fully functional 3D printer can print a high-resolution model that can be colored directly after printing to give it the appearance of the final product, which also enables designers to see and touch the final product before production. Taking Peltor's products as an example, Peltor has more than 50 years of experience in the development and manufacturing of hearing protectors. They focus on the functional and aesthetic needs during the development process and the need to simulate the material and function of the final product for testing. Peltor uses 3D printing technology to achieve product simulation, and they fill the 3D printer with special materials before mass production, which replaces the material of the final product.

Component 2: Optimize the construction process enabling CSFs

Component 2 consists of 3 CSFs including "creating safer work environments and can reduce health and safety risks", "reduced construction time" and "mass customization of building components". This component is related to the indicators of the construction process such as cost, time, and safety requirements. As such, this component is categorized as "optimize the construction process enabling CSFs". Its total variance accounted for 25.207%.

The construction processes and raw materials used during traditional construction projects cannot respond to government and market demands for green construction and efficiency, which add barriers to achieving green innovation in the construction phase of a project. Compared to traditional construction projects, 3D printing technology can be used to produce components that require special equipment and highly polluting materials (Sakin & Kiroglu, 2017), thus reducing material waste and time during the construction and installation process of traditional construction processes. Sakin and Kiroglu (2017) stated that 3D printers can replace most dangerous workplace activities and reduce the number of injuries on construction sites, thus providing a safe environment for enhancing workers' health and safety. From the perspective of sustainability requirements, clients need innovative and green architectural structures. Designers and architects are required to recreate innovative components that meet structural and site requirements, upending traditional construction processes with low material utilization. Software developments underpin the exploration of the true potential of 3D printing technology (Sakin & Kiroglu, 2017). 3D printing technology creates the possibility for mass customization of building components. Architectural 3D printers are 3D printing devices specially designed for the construction industry, which can be integrated with computer modeling software to build customized products more accurately and timely. 3D printing technology may neither require practitioners to relearn, nor require expensive equipment maintenance. It often needs the use of modeling software to draw 3D models, while showing the detailed installation process and functions of the product from a visual perspective. Zortrax, a Polish company, used 3D printing technology for standardized production (Zortrax, 2017). It can improve the coordination and communication between practitioners to better understand client's needs (Srinivasan *et al.*, 2016), and produce products that meet customers' requirements, which can reduce pollution caused by repeated production to some extent. 3D printing technology has the potential to meet the needs of customers/clients by ensuring faster delivery throughout all stages of construction projects. ApisCor, for example, used a mobile printer to print a 400-square-foot house in Russia in 24 hours. 3D printing technology brings automation to onsite construction, thus increasing the delivery and customization of construction. The use of 3D printing technology can reduce the construction time for structural components, thus significantly reducing the overall construction period (El-Sayegh *et al.*, 2020).

Component 3: Optimized design enabling CSFs

Component 3 involves three CSFs such as "move design and production departments away from paper-based digital models", "increase the design freedom of complex building" and "earlier detection and reduction of design errors". These 3 CSFs emphasize the green innovation of 3D printing technology in the design phase. Consequently, it was referred to as "optimized design enabling CSFs". The total variance of this component is 24.714%.

Design is one of the key stages of a construction project. Automation techniques can be applied to the early stages of design, including geometry, spatial structure, and conceptual design, as well as to further design and implementation plans (Shi *et al.,* 2020). The combination of modeling systems and 3D printing technology allows for satisfactory management of design parameters (Shi *et al.*, 2020). 3D printing technology can refine project parameters and form 3D models to optimize designs. 3D printers can scan 3D data of a project, apply material layers, and then combine it to form a building product. This technology can satisfy the design of almost any shape. The freedom to design buildings with complex shapes could be one of the advantages 3D printing technology brings to designers, whose imagination can break through the limitations of traditional architectural techniques and fully consider the sustainable issues of design, structure, and materials (Sakin & Kiroglu, 2017). The use of 3D printing technology enables construction practitioners (e.g., architects, engineers, contractors, clients, and executors) to achieve information sharing and joint participation in building design (Aghimien *et al.,* 2020; Doloi, 2013). Automated technologies such as 3D printing technology can filter design solutions according to stakeholders' needs (Shi *et al.*, 2020). Building structures should not only be designed for long-term operation, but also should meet green innovation features. BIM can create 3D models of buildings or components while acquiring and controlling environmental, cost, time information, etc. (Antwi-Afari *et al.,* 2018). The integration of 3D printing technology and BIM gives the design team the ability to control complex events, adjust system parameters and regulate the demands of multiple practitioners (Shi *et al.*, 2020). The integration of these two advanced information technologies can also facilitate the paperless process in the design phase. They can meet the need for multiple revisions of complex designs in a short period of time and respond to project requirements such as time, quality, cost and safety (Sakin & Kiroglu, 2017).

Design errors are inevitable in the design process, but they may lead to material waste, production failure, and other issues (Baumann & Roller, 2016; Ham *et al.*, 2018; Love *et al.,* 2011; Peansupap & Ly, 2015), which are non-value-added activities that do not meet the needs of green innovation and development (Ding *et al.*, 2019). For the traditional design process, dimensional errors and spatial conflicts in engineering design are basically only discovered after an on-site inspection. 3D printing technology and BIM application can facilitate design inspection and process. BIM can eliminate these types of design errors through built-in collision detection (Love *et al.,* 2011). Collision detection is an early-stage detection method that accelerates projects by identifying conflicts between models at the design stage, assisting project practitioners to eliminate the impact that can lead to multiple design changes (Abd & Khamees, 2017; Chahrour *et al.,* 2021). Since the complete building contains multiple design models, construction practitioners (e.g., architects, structural engineers, MEP engineers) can create independent design models for printing (Abd & Khamees, 2017; Ding *et al.*, 2019). All models can be integrated into the BIM modeling process whilst performing collision detection prior to printing. It would ensure that there are no incompatibilities between design models and elements, allowing project practitioners to detect conflicts at the earliest stages of design (Sampaio *et al.*, 2017). It makes all elements in the model cooperate with each other, reduces changes in the construction phase, eliminates information gaps between practitioners, and enables all departments to work together effectively (Abd & Khamees, 2017), simplifying the design process to improve design efficiency.

Theoretical and practical contributions of this study

Firstly, the results of this study provide useful guidance for process optimization in the construction industry. This study identified the key interventions (i.e., CSFs) needed for implementing 3D printing technology in construction projects. The findings suggested the ways and boundaries in which 3D printing technology can be used in the construction industry and concluded that it improves the efficiency, quality, and accuracy of information transfer among construction practitioners (e.g., engineers, architects, project managers, etc.). This would broaden stakeholders' awareness of the potential benefits of adopting 3D printing technology. As such, it would increase the rate of practical implementation of 3D printing technology in the construction industry, enabling rapid and sustainable growth.

Secondly, this study focuses on the optimization role of 3D printing technology in the design, construction, and post-construction stages of projects. It would further refine the innovative applications of 3D printing technology and provide practitioners with specific technical information. This would entice other stakeholders to conduct targeted follow-up research on 3D printing technology, enhancing a favorable technological environment to maximize the use of advanced information technologies to optimize the construction lifecycle processes.

Finally, the results of the study would not only provide a theoretical reference for other researchers to conduct further studies on the implementation an applications of 3D printing technology in construction projects but also provide practical contributions to construction practitioners on the potential benefits of using sustainable materials for constructing building elements/products.

Conclusions

The slow adoption of 3D printing technology in construction projects emphasizes the relevance of studying its implementation based on academic and construction practitioners’ perspectives. This study aims to explore the academics and practitioners’ perspectives on CSFs for implementing 3D printing technology in construction projects. Through a comprehensive literature review, 20 success factors were identified. A survey was conducted, and a questionnaire was administered to participants (i.e., academics and construction practitioners) with knowledge and expertise in 3D printing technology in construction projects. Twenty-five valid responses were analyzed using mean score ranking, normalization, rank agreement analysis, and exploratory factor analysis.

The results showed that out of 20 success factors, only 11 intervention factors were key CSFs for implementing 3D printing technology in construction projects. The five highly ranked CSFs include: “improved ability to visualize part geometry” (SF05), “make it easy to develop a model or prototype” (SF19), “increase the design freedom of complex building” (SF02), “earlier detection and reduction of design errors” (SF06) and “convenient for form, fit, and function testing” (SF11). In addition, respondents (i.e., academics and construction practitioners) had a low agreement rate on the ranking of the 11 CSFs. Finally, the results from exploratory factor analysis identified the relationships and underlying constructs of three basic components including “production demand enabling CSFs”, “optimize the construction process enabling CSFs” and “optimized design enabling CSFs". The findings of this study would serve as a reference for other researchers interested in 3D printing technology research and increase construction practitioners' awareness of the practical benefits of implementing 3D printing technology in construction projects. By identifying, ranking, and classifying the key CSFs for implementing 3D printing technology in construction projects, the findings would contribute to achieving a rapid, sustainable, and digitalized construction industry. In addition, this study provides a theoretical contribution to advancing digital transformation, high-quality and efficient reforms in construction projects.

Despite the contributions of this study, there are some limitations worth addressing in future studies. First, although 73 questionnaires were administered during the survey, only 25 completed questionnaires were used for further analyses which constituted a small sample size. It is suggested that follow-up studies could increase the sample size to enhance the generalization of the findings. Second, a list of 20 success factors was identified and discussed through a comprehensive literature review. Consequently, only 11 key CSFs were established for implementing 3D printing in construction projects. 3D printing technology could be adopted in other fields like civil engineering, biomedical engineering, and among others, thus, future studies should expand the success factors to other fields to improve the reliability and validity of the findings. Third, the respondents of this study were only academics and construction practitioners. While the findings suggest more targeted research and development as well as construction practitioners' awareness, other stakeholders such as private investors, government departments, and regulatory sectors are missing. It is recommended that future studies should extend the target respondents to the stakeholders to increase their awareness and adoption of 3D printing technology.

Declarations of interest

No potential conflict of interest was reported by the authors.

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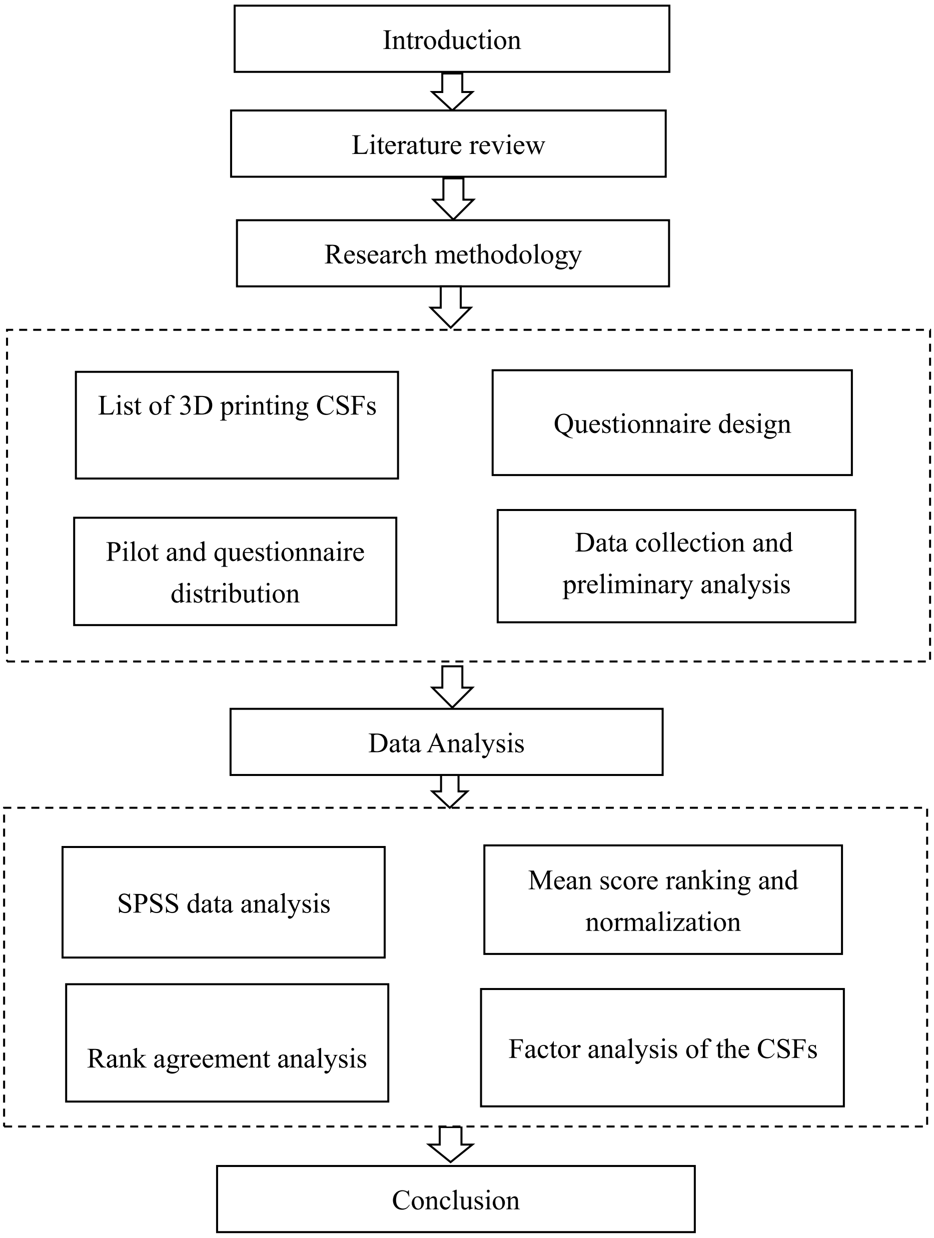

Figure 1. Research framework. Source: Created by authors

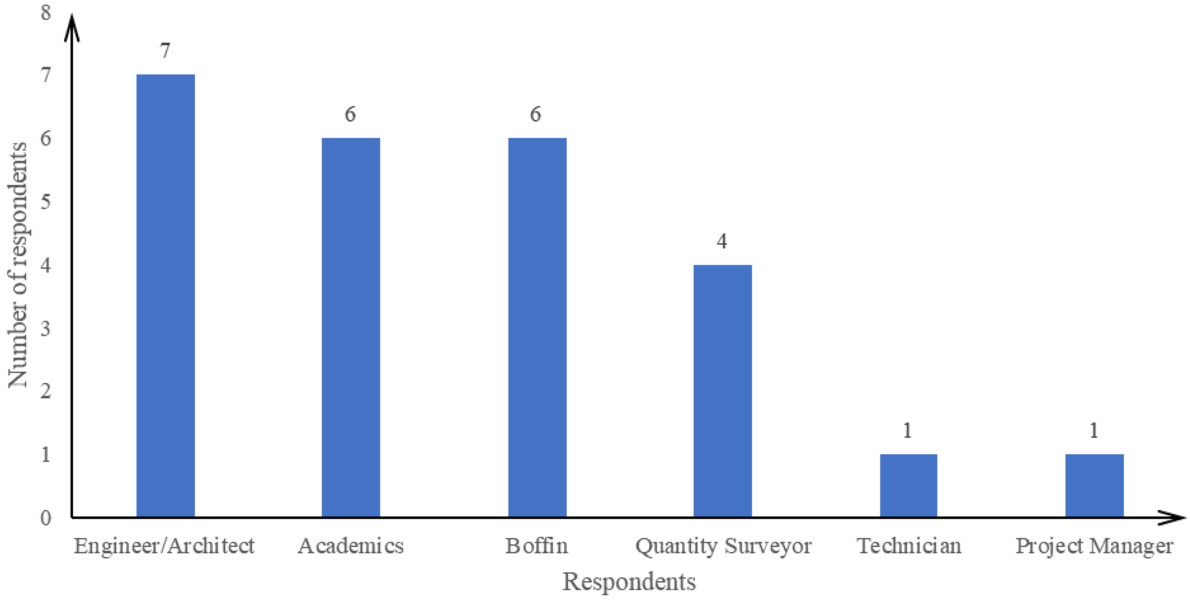

Figure 2. Position distribution of the respondents. Source: Created by authors

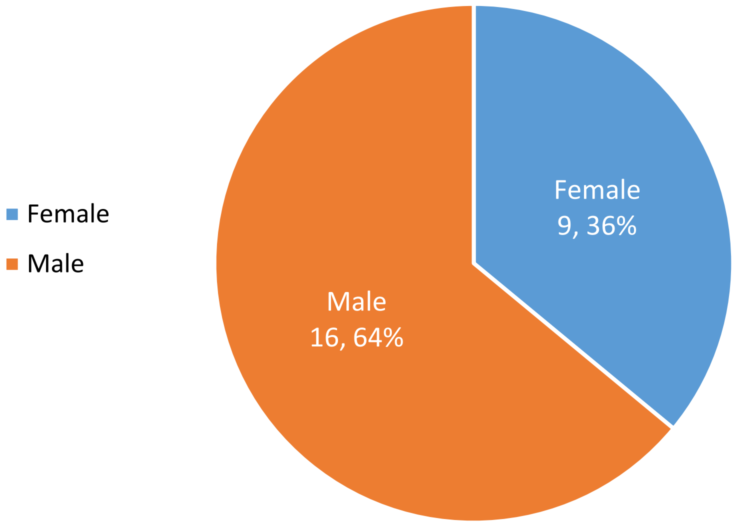

Figure 3. Gender distribution of the respondents. Source: Created by authors

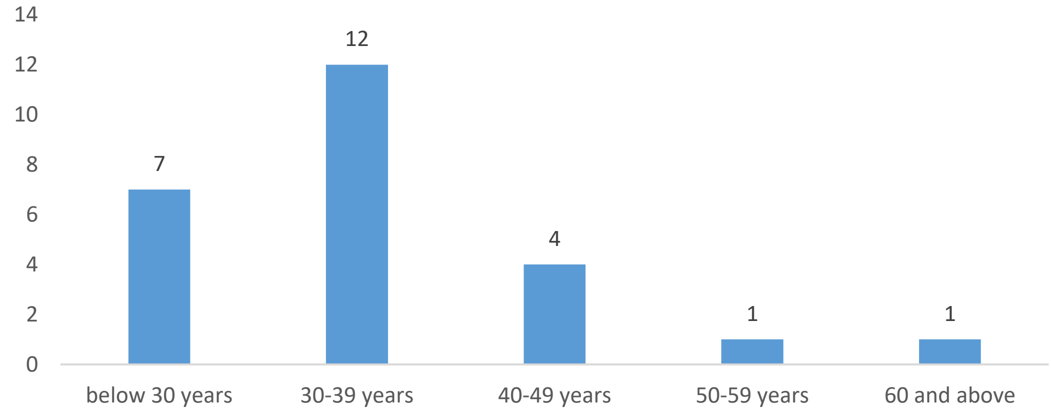

Figure 4. Age distribution of the respondents. Source: Created by authors

Table 1. List of success factors (SFs) for implementing 3D printing technology

Codes	Success Factors	References
SF01	More flexible manufacturing process	He et al., 2021
SF02	Increase the design freedom of complex building	De Schutter et al., 2018
SF03	Move design and production departments away from paper-based digital models	Dadi et al., 2014
SF04	Mass customization of building components	De Schutter et al., 2018
SF05	Improved ability to visualize part geometry	Godoi et al., 2016; Sangiorgio et al., 2022
SF06	Earlier detection and reduction of design errors	Han et al., 2012
SF07	Increased capability to compute mass properties and assemblies	He et al., 2021
SF08	Communication of product characteristics	He et al., 2021
SF09	Facilitate meeting schedules and making milestones	Beltagui et al., 2020
SF10	Tooling for injection molding	Dizon et al., 2019
SF11	Convenient for Form, fit, and function testing	Greder et al., 2020
SF12	Engineering change clarification	Ma, 2020
SF13	Solve labor shortage	Guimaraes et al., 2021; Hossain et al., 2020
SF14	Creating safer work environments and can reduce health and safety risks	Buchanan & Gardner, 2019; Ning et al., 2021
SF15	Reduced construction time	Buswell et al., 2007
SF16	Increased durability of buildings	Grassi et al., 2019
SF17	Client presentations and consumer evaluations	Shahrubudin et al., 2019
SF18	Reduce the total project cost	Hossain et al., 2020; Guimaraes et al., 2021
SF19	Make it easy to develop a model or prototype	Buswell et al., 2007
SF20	Reduce material waste	Guimaraes et al., 2021; Hossain et al., 2020

Source: Created by authors

Table 2. Ranking of critical success factors (CSFs) for implementing 3D printing technology

Codes	**Respondents (ALL)**			
	Mean	**SD**	**Normalization**	**Rank**
SF05	4.20	0.816	1.00*	1
SF19	4.12	1.054	0.93*	2
SF02	4.04	0.889	0.87*	3
SF06	4.04	0.978	0.87*	3
SF11	3.92	0.954	0.77*	5
SF01	3.80	1.041	0.67*	6
SF10	3.80	0.957	0.67*	6
SF03	3.76	1.052	0.63*	8
SF14	3.76	0.926	0.63*	8
SF15	3.76	0.970	0.63*	8
SF04	3.60	1.080	0.50*	11
SF08	3.44	1.325	0.37	12
SF18	3.40	1.258	0.33	13
SF20	3.40	1.258	0.33	13
SF07	3.32	1.249	0.27	15
SF12	3.32	1.145	0.27	15
SF13	3.28	1.242	0.23	17
SF09	3.16	1.375	0.13	18
SF17	3.16	1.248	0.13	18
SF16	3.00	1.291	0.00	20

Note: SD = Standard deviation; $\overline{X}$=Mean.

Normalized value = $\frac{\overline{X}-\overline{X}_{min}}{\overline{X}_{max}-\overline{X}_{min}}$

* Indicates that the success factor is critical (i.e., normalized values ≥ 0.50).

Source: Created by authors

Table 3. Agreement analysis on ranking of critical success factors (CSFs) for implementing 3D printing technology

Code	Academics			Construction practitioners			Agreement analysis		
	Mean	**SD**	**Rank**	**Mean**	**SD**	**Rank**	$\mathbf{R_i}$	$\mathbf{D_i}$	$\mathbf{\lvert R_{i1} - R_{j2} \rvert}$
SF01	4.08	0.79	6	3.54	1.20	7	13	1	2.273
SF02	4.25	0.75	1	3.85	0.99	4	5	3	5.727
SF03	3.92	1.08	11	3.62	1.04	6	17	5	6.273
SF04	4.08	1.00	6	3.15	0.99	11	17	5	6.273
SF05	4.25	0.87	1	4.15	0.80	1	2	0	8.727
SF06	4.17	0.94	3	3.92	1.04	3	6	0	4.727
SF10	4.08	0.90	6	3.54	0.97	7	13	1	2.273
SF11	4.00	1.04	10	3.85	0.90	4	14	6	3.273
SF14	4.17	0.94	3	3.38	0.77	9	12	6	1.273
SF15	4.17	0.72	3	3.38	1.04	9	12	6	1.273
SF19	4.08	1.24	6	4.15	0.90	1	7	5	3.727
								$\sum_{i=1}^{N} D_i$ =38	$\sum_{i=1}^{N}(\lvert R_{i1} - R_{j2} \rvert)$=45.818

Source: Created by authors

Table 4 Component matrix

Code	**Components**		
	1	**2**	**3**
SF5	0.79	-	-
SF19	0.706	-	-
SF2	0.727	-0.511	-
SF6	0.791	-	-0.514
SF11	0.758	-	-
SF1	0.785	-	-
SF10	0.822	-	-
SF3	0.798	-	-
SF14	0.804	-	-
SF15	0.754	-	-
SF4	0.552	0.748	-

Extraction method: Principal component analysis

3 components have been extracted

Source: Created by authors

Table 5. Components of the critical success factors (CSFs) for implementing 3D printing technology

Codes	CSFs for implementing 3D printing technology	Components		
		1	**2**	**3**
Component 1	**Production demand enabling CSFs**			
SF05	Improved ability to visualize part geometry	0.831		
SF19	Make it easy to develop a model or prototype	0.708		
SF11	Convenient for form, fit, and function testing	0.821		
SF01	More flexible manufacturing process	0.732		
SF10	Tooling for injection molding	0.507		
Component 2	**Optimize the construction process enabling CSFs**			
SF14	Creating safer work environments and can reduce health and safety risks		0.719	
SF15	Reduced construction time		0.751	
SF04	Mass customization of building components		0.914	
Component 3	**Optimized design enabling CSFs**			
SF03	Move design and production departments away from paper-based digital models			0.595
SF02	Increase the design freedom of complex building			0.782
SF06	Earlier detection and reduction of design errors			0.903
Eigenvalue		6.300	1.397	0.982
Variance (%)		28.983	25.207	24.714
Cumulative variance (%)		28.983	54.190	78.903

Extraction method: Principal Component Analysis.
Rotation method: Varimax with Kaiser Normalization.
Rotation converges after 6 iterations
Source: Created by authors