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3D Printed Housing Architectural Design Principles

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ABSTRACT: This article explores the design principles for building houses with 3D printers. This study provides an overview of the architectural principles needed to design houses using this technology. The absence of these foundations can cause unsuitable designed forms for this technology. The analysis in this research includes a wide range of relevant articles, and we have found many approaches to the architectural design of 3D-printed houses. This review addresses many aspects of materials, printer types, construction sites, structures, and architecture. The results of this research will help architects understand the dos and don'ts of designing these kinds of housing and raise awareness in the design phase. Moreover, it will prevent errors during construction.

In conclusion, constructing houses with 3D printers is the best for small one-story houses. Houses with hand-reinforced concrete and glass fibers in curved forms have a free plan designed by digital design. The point that must be added is that by combining structural systems with traditional roofs, we can add to the number of floors, allowing us to use more of this technology.

Keywords: *Housing Construction, House 3D Printing, Digital Fabrication, Mass Customization, Architectural Design Criteria.*

INTRODUCTION

The construction industry constitutes about 13% of the gross product of the countries of the world, and this number is expected to increase by 6% in the next five years due to the rapid growth of urbanization (Valente Sibaji et al., 2019), due to the construction industry in the world, the economic and environmental effects of this industry cannot be ignored. In other words, a small change to improve construction methods can greatly impact the construction process. On the other hand, developing countries are facing problems such as housing shortage, rapid urban expansion, and lack of infrastructure for future generations (Du Plessis, 2002). It must be considered that 21st-century problems like unbridled population growth, environmental pollution, lack of energy, lack of suitable land, and affordable housing cannot be solved with 20th-century solutions (Summary, 2019). A desirable solution for housing construction is a model that combines the advantages of industrial construction methods with the advantages of conventional and non-industrial housing construction processes. We assume that building housing with 3D printers will soon be a conventional method and an inevitable choice to provide housing needed by communities (Kashani et al., 2018). Construction made with 3D printers shows the capacity of automatic technologies for constructing buildings through additive manufacturing methods. By focusing on the construction of housing with 3D printers as an alternative method for the construction of mass housing, this research Vladimir and his colleagues, in an article entitled "Future House Building, the Fourth Industrial Revolution," have examined the opportunities and limitations of building houses with 3D printing systems and concluded that this technology has a deep impact on architectural design research and the house production process. It also significantly reduces the overall investment, time, resources and consumables, labor force, and pollution (Lojanica et al., 2018).

Since the buildings built with 3D printing offer various combinations, it seems necessary to investigate the architectural features of these buildings to construct similar structures with this technology in the future (Garcia-Alvarado et al., 2021). The expansion of housing construction with 3D printers, besides facilitating the use of this technology, is necessary to pay attention to explaining the architectural design characteristics for this construction method. Despite the expansion of construction technology with 3D printing, a written framework in the architectural features of houses that are supposed to be built with this technology was not found in most of the research as other construction systems, such as tunnel mold or cold rolling systems need to observe some things in their architectural design. Buildings

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with 3D printing technology have requirements for architectural design that should be taken into consideration by designers, which has been given less attention in studies and is more focused on the technical aspects of building with this technology. The field of 3D printing on a large scale for the construction of housing and awareness about the architectural features of this housing model was a motivation for this research to achieve a model in which the limitations and potentials of the design of these buildings to maximize the use of the capabilities, provide incremental construction technology for housing and other constructions. According to the purpose of this research, the research question can be explained as follows: What should be considered in architectural design in the design of houses that will be built with 3D printing technology?

MATERIALS AND METHODS

Due to the novelty of the subject, almost all the valid articles related to the research questions in the last ten years, which were about one hundred and forty articles, were extracted to conduct a systematic study and review of the research literature. Systematic review is a suitable tool for determining the boundaries of existing research on a problem. To review the articles, we have been searching for five items in the branches related to the research questions. These five items include suitable materials for building housing with 3D printing, the suitable system for building housing with this method, the construction site, the structure and type of building reinforcement, and architectural features used in the study. Systematic review was done by selecting reliable databases, including Google Scholar, Scopus, and Science Direct, which were reviewed to cover the sources between 2010 and 2023. The search was done in these three databases using the combination of two words: 3D printed housing, additive manufacturing for housing construction, architectural aspects of 3D printed building, and 3D printed building design. After the initial search of the databases, a total of 976 relevant articles were retrieved. In the beginning, duplicate items were removed, the title and abstract of the remaining 893 articles were carefully studied, and unrelated articles were removed from the process. Finally, the full text of possible related articles was reviewed, and 138 articles were selected to review the components. Figure (1) shows the details of this process based on the Prisma flowchart (Page et al., 2021). We extracted the articles from the databases based on related keywords to the research, and after the initial review, the articles that were not related to the topic and the research questions, or it was not possible to access their full text, were removed from the list of articles. To avoid bias in selecting and removing articles, the sources were reviewed by two researchers independently of each other. After sharing the results, if there was a difference of opinion regarding the removal or selection of articles, the third researcher reviewed them and made a decision. After collecting the articles, a Meta-synthesis approach was adopted to extract effective components in the design of housing made with 3D printing technology.

Meta-synthesis is a qualitative method based on a systematic review of library studies for a deep understanding of the studied phenomenon. The Meta-synthesis method is a qualitative research method whose data collection tool is library studies and research background investigation (Pooya et al., 2020). Sandelowski and Barroso's meta-synthesis model was used in this research. Sandelowski and Barroso's method is a coherent model of meta-synthesis that examines information and findings extracted from other studies on a related topic. This method provides a systematic approach for researchers by combining different qualitative research and discovering new and fundamental themes and metaphors (Sandelowski & Barroso, 2006). This model includes seven steps as follows: 1- Setting the research question, 2- Systematic review of the literature, 3- Searching and selecting suitable texts, 4- Research information extraction, 5- Analysis and synthesis of data, 6 - Quality control and 7- Presentation of findings (Sandelowski & Barroso, 2006). Regarding the reliability of the research and the level of agreement between the two coders, Cohen's kappa coefficient method was used, that for the present research, this coefficient is between 0.80-0.90, which represents 64% to 81% of the validity of the qualitative analysis (Carletta, 1996).

Research Background

The method of constructing with 3D printers using layered concrete was first proposed by Khoshnavis and his colleagues at the University of California (Khoshnevis et al., 2006).

In an article titled "Additive construction in the construction industry: examining the competitiveness of concrete 3D printing", Siavash Khajovi and colleagues consider additive construction and 3D printing as a solution to improve housing production and reduce environmental impacts. By defining seven different scenarios in house design and construction, they have concluded that using 3D printing in construction (especially for irregular, non-repetitive, and complex forms) can significantly reduce time and cost. They recommend using a robotic arm in situ for 3D printing compared to other methods (Khajavi et al., 2021). In an article entitled "Providing a framework for building housing with 3D printing in South Africa", Douglas Agieman and his colleagues, through the review and analysis of related factors, have found out that 3D printing in housing construction reduces costs, increases productivity, Investors satisfaction, and socio-economic benefits have increased the quality of delivery and construction.

Along with these advantages, there are disadvantages, such as technical and operational issues of 3D printing, organizational and personal issues, and a lack of awareness and understanding of 3D printing technology among investors and buyers to use this technology fully (Aghimien et al., 2020). In an article titled "3D printing technology, a solution towards designing sustainable and cheap housing", Amir Abu Alalla and his colleagues examine the upcoming challenges for supplying sustainable and affordable housing and consider 3D printing technology a solution. Using descriptive, analytical, and experimental research methods, the authors provide a solution for designing affordable houses. This solution is compatible with unfavorable weather conditions and reduces the time required to construct and design free forms (Abouelela & Ali, 2021). In the figure below, Nadarajah (2018) explains in his research how 3D printing can reduce costs and increase speed by integrating several manufacturing stages (Fig 2).

In the article "Additive manufacturing in the construction industry"

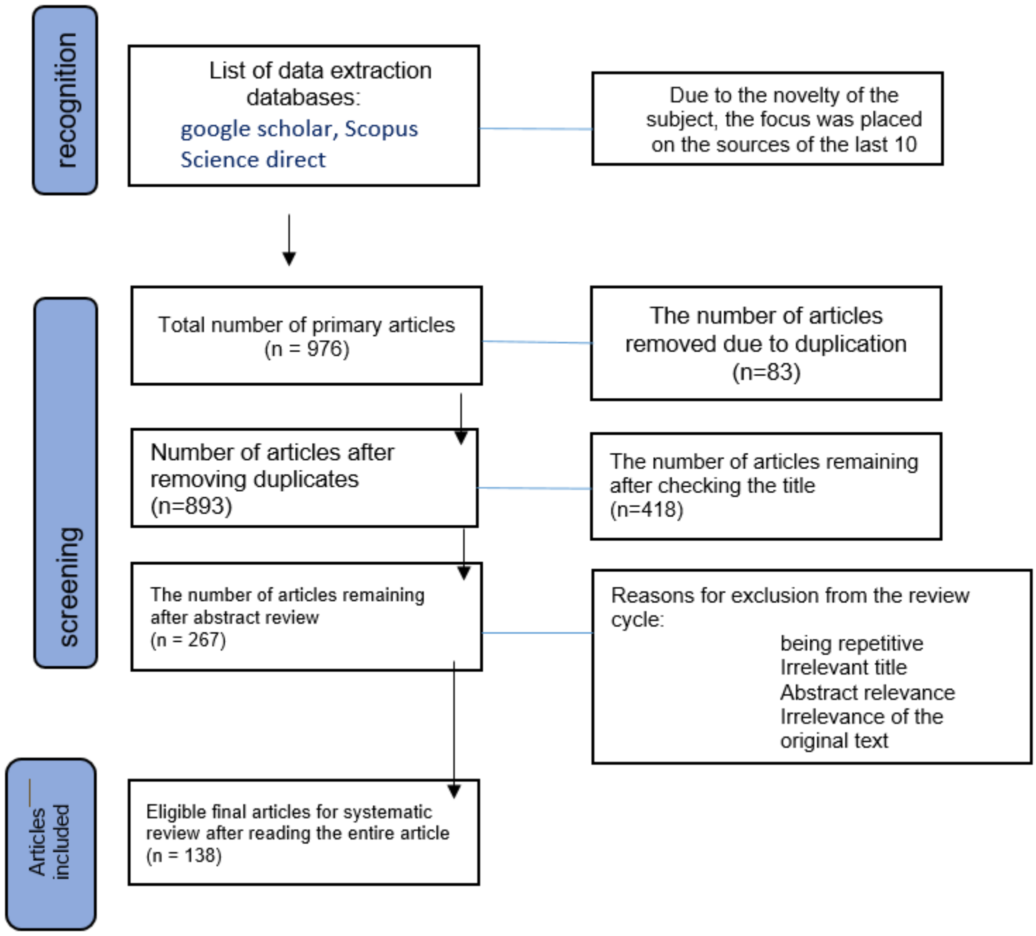

Fig 1: Diagram of the process of identifying studies through databases

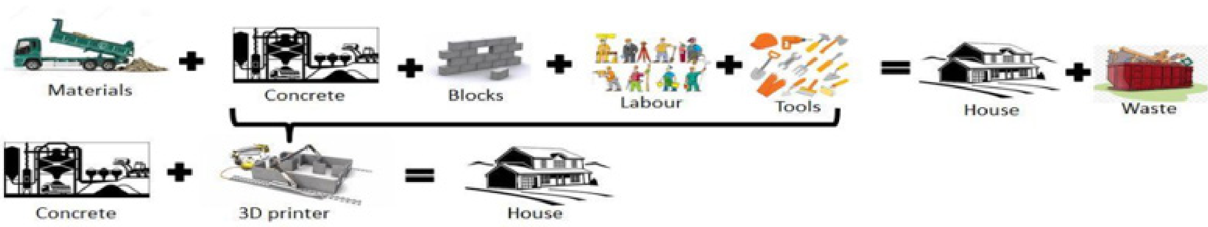

Fig 2: Integration of manufacturing steps in 3D printing (Nadarajah 2018)

(Khajavi et al., 2021), the authors state that constructing round walls with 3D printing technology is more cost-effective than other methods. In the article "Development of walls in residential buildings with 3D printing technology" (García-Alvarado et al., 2022), it is stated that non-structural elements and partitions and creating different arrangements with printed elements in the structural network It is done because the formal capabilities of 3D printing technology are more than conventional methods. In the paper "Towards Automated Manufacturing: Design-to-Print Workflow for an On-Site Robotic 3D Printing House" (Xu et al., 2022), the author concluded that a six-axis robotic arm printer for manufacturing more complicated forms is suitable, but it has smaller construction dimensions than the gantry printer. In the article "Investigation of 3D Printing Trends in the Building and Construction Industry" (Tay et al., 2017), the authors have concluded that in construction with 3D printers, as concrete collapses from more than a definite slope number, we face the limitations of construction with protruding sections and arches that should be taken into account in architectural design. The article "Application of Additive Manufacturing in the construction industry - a prospective review" (Camacho et al., 2018) points out that this technology is suitable for mass customization without imposing additional costs on the manufacturing process. In the article "Architectural Evaluation of 3D Printed Buildings" (García-Alvarado et al., 2021) architectural features, it is stated that orthogonal shapes with rounded corners and curved clastic and anticlastic walls are suitable for construction with this technology. Also, many small breaks in the plan are not recommended. In addition, arched walls have better structural stability, but it is more difficult to furnish and install equipment and facilities. Also, 3D printing is more suitable for building detached and continuous single-story houses based on load-bearing walls. The article "3D Printing in the Construction Industry" (Perkins & Skitmore, 2015) says that creating completely perpendicular corners is undesirable and difficult to do using this method. The article "Critical review of 3D printing in construction: advantages, challenges and risks" (El-Sayegh et al., 2020) states that the location of the facilities must be considered in architectural design because otherwise, We have demolition after construction for these cases. In the article "A Review of 3D Printing in Construction and its Impact on the Labor Market" (Hossain et al., 2020), it is stated that it should be noted that the reinforcement limits the size of the architectural forms, and although in terms of printing technology, many forms can be built if you need to reinforce and enter the cage and reinforcement network into the volume, you have to refrain from designing and creating extreme curves and volumes where it is difficult to enter the reinforcement. In the article "3D printing in Architecture: One Step Closer to a Sustainable Construction Environment" (Beyhan & Arslan Selçuk, 2018), it is stated that the construction limit is determined according to the properties of the materials and the rheology rate and cannot be applied to all materials and Printer types and forms.

Systematic Literature Review

Studying the comprehensive review of the basics of 3D-printed housing includes some key steps. First, we have adopted a systematic approach to ensure a perfect and fair search for relevant studies, articles, and publications. This process involved using specific search terms and criteria to identify various sources. Next, we screened these sources based on their relevance to the research topic. Once we found relevant literature, we analyzed it to extract key information and parameters. This analysis of the research questions stemmed from the findings and limits of each study. We will examine the mentioned components and the resulting data in the following.

Materials

In 3D printing buildings, we use highly productive and efficient materials. These materials are suitable. They must resist pressure, be flexible, and resist weather conditions to be formed clearly and remain sustainable and resistant. Building materials usually include concrete, metals, plastics, and wood. These materials build different parts of the building.

In the study of the mentioned articles about materials, Researchers observed that concrete accounts for about 76% of different types. 10% are of vernacular materials, such as mud, soil, and wood. 5 % are recycled materials like plastic, concrete, and wood. And 9% are of other materials (Fig 3).

Printer System

In 3D printing a building, the choice between using a gantry system or a robotic arm is crucial. Each system has its pros and cons that should be considered before making a decision. The gantry system is a popular choice for 3D printing large structures because of its ability to cover a large area (Kashani et al., 2018). A gantry is a fixed system that moves along a set of rails and allows accurate printing. However, it may not be as flexible as a robotic arm system that can move in different directions and angles (Fig 4).

Puzatova, Shakor, and their colleagues state that a robotic arm system provides more flexibility and can print complex shapes and designs (Puzatova et al., 2022). The study of the mentioned articles about the printer systems used found that 48% used the gantry printer, 45% used the robotic arm printer, and 7% used other systems (Fig 5).

Structure

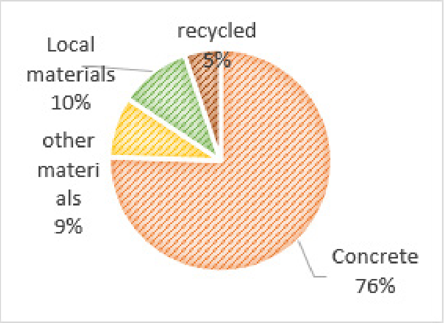

Fig 3 The percentage of materials used in the systematic review of research literature

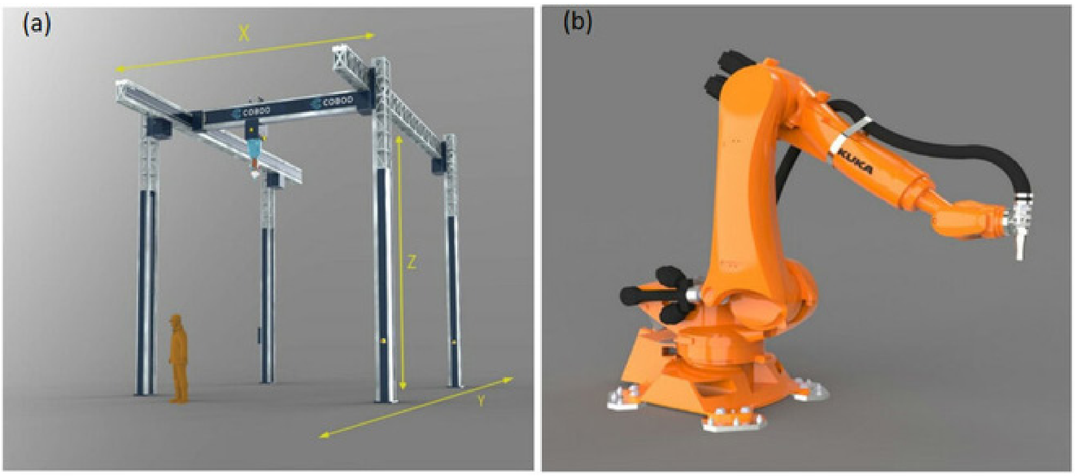

Fig 4: gantry printer (a) Robotic arm printer (b) - (Aboelhassan 2023)

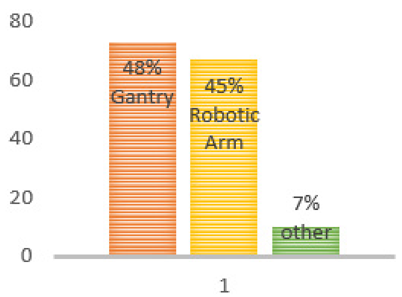

Fig 5: The percentage of using different 3D printer systems in the systematic study of research literature

Reinforcement techniques are important. They increase the strength of 3D-printed buildings. As 3D printing technology is being developed, buildings built with this technology must be able to resist powerful forces without collapsing as conventional ones. One of the common methods of reinforcement includes the addition of extra materials in the printed layers. Steel rods can be placed inside the printed structure to increase strength and stability. Moreover, steel bars or fiber-reinforced polymers boost the printed structure's strength. They make it more durable and able to bear more load capacity.

In the study of the mentioned articles in reinforcement and structure, it was observed that about 48% of cases used all three methods (adding fibers and other concrete additives, manual rebar installation, and using stable geometry). 28% just added fiber and other concrete additives. 7% just added rebars manually. 8% used stable geometry, and 9% used other methods (Fig 6).

Architecture

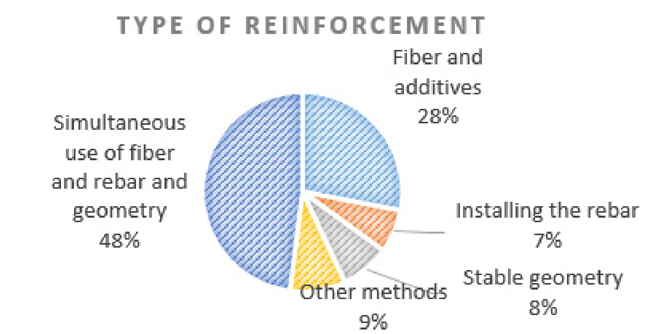

Fig 6: The percentage of the type of reinforcement in the systematic study of research literature.

Designing a 3D-printed building requires unique considerations and a different approach than normal architectural design. While designing a building for 3D printing, architects must consider the limits and abilities of the technology and the project's specific needs. Unlike usual construction methods, 3D printing enables building complex shapes and structures that were hard or impossible before. This creates new opportunities for architectural design. However, it also needs a new mindset (Davydenko & Melyushchenko, 2022). 3D printers have size limits, so architects should carefully consider the building size they are designing. Besides, the materials used in 3D printing can vary in strength, durability, and appearance. Architects have to choose suitable materials for the buildings' needs. They also have to consider cost and sustainability. Moreover, the designers have to consider the building's structure, the space's function, and the aesthetic factors of the space. Although 3D printing provides more design freedom, it's important to ensure the building is strong and meets safety standards (Fig 7).

In the study of the mentioned articles in architecture, the data found divided into three categories as follows:

A) Limiting elements of form and plan, B) features of form and plan, C) special applications of this method.

A) Limiting elements of form and plan, which will be built using 3D printing in the articles, is as follows (Fig. 8). Reinforcement is 13%, facilities 16%, printer size and its effect on construction dimensions is 25%, material properties 9%, and the need for support is 25%. The limit for large and small breaks and vertical corners is 12%.

b) The plans' 3D printing features and frequency in the articles are as follows (Fig 9). Curved walls are 25%. Geometric and plan freedom are 15%. Complex forms are 25%. Rounded corners are 8%. Self-standing and domed forms are 12%. Stable structural geometry is 15%.

C) This method has special uses in design (Fig 10). Walls and non-structural elements and combining with other constructing methods (20%). No need for concrete molding (10%). Mass customization (30%). Making structures, architecture, furniture, and decorations (15%). Small buildings, emergency housing, and pavilions (25%).

RESULTS AND DISCUSSION

Fig 7: Tekla project built with native materials and self-standing roof form by wasp (Moretti, 2023)

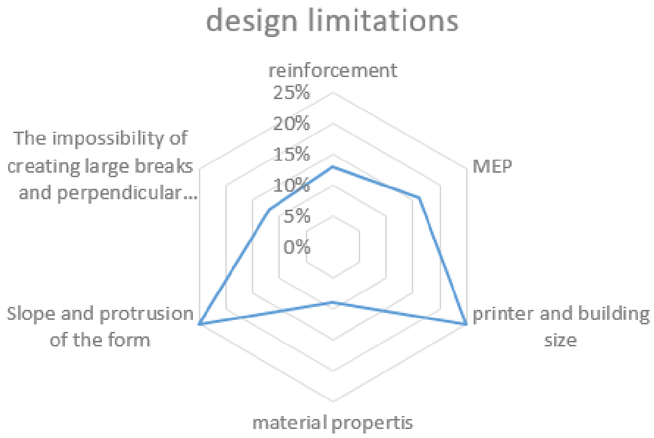

Fig 8: The frequency of design limitations in the systematic study of research literature.

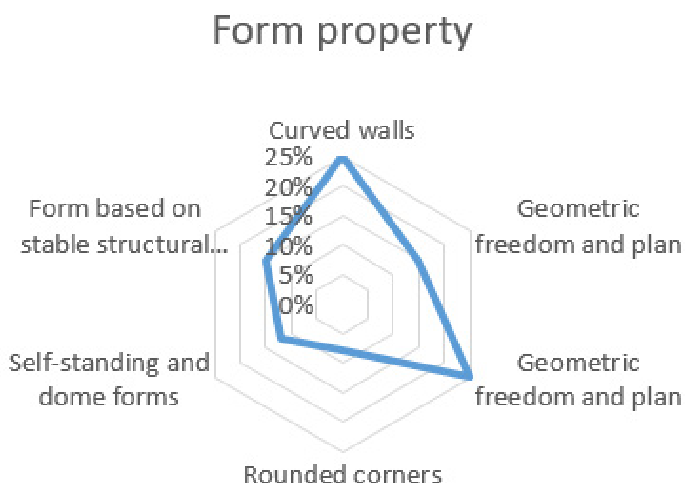

Fig 9: The frequency of form features in the systematic study of research literature.

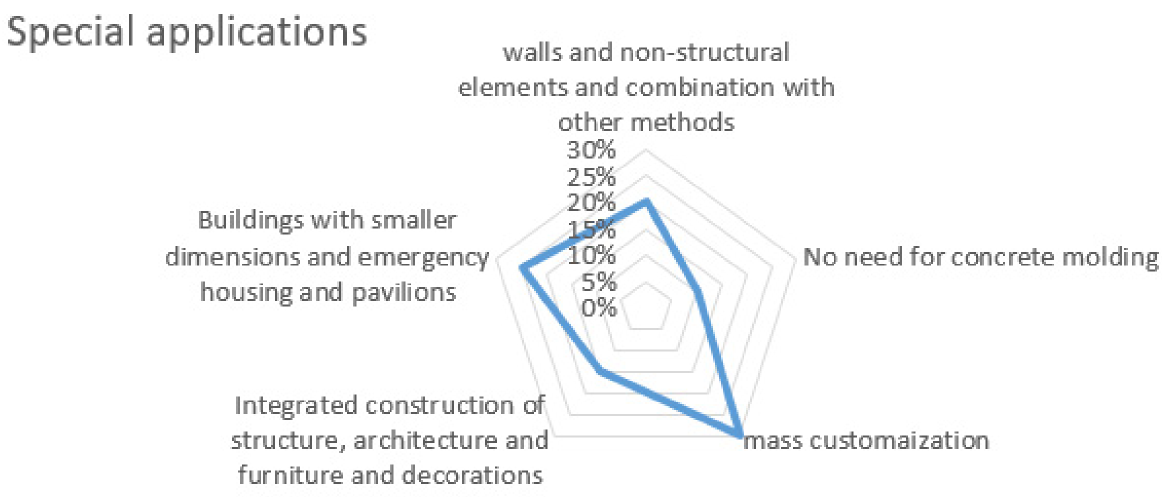

Fig 10: Frequency of special design applications for 3D printing in the systematic study of research literature.

This research provides a conceptual framework of effective items and components in the design of housing built with a 3D printer. This framework results from a systematic study of the research literature regarding the architectural features of this type of housing. In the diagram, the principles mentioned in this article are presented as a conceptual framework (Fig 11).

In the following, in line with the discussion about the relationship of the components, we organized them in the form of the following matrix. This matrix has four sides, each with variables defined in a specific range (Fig 12).

As we can see in the matrix above, with the change in the type and size of the components and the extension of this change in the matrix framework and the middle diagram, the proposed conditions for other variables are specified. The initial diagram can be considered a diagram of the dimensions of the units. We examine this matrix in two cases. First, in the situation where the dimensions of the units are large, in this case, as you can see in the matrix, it is recommended that the complexity and curvature of the form be low, the print system be the gantry system and built on site. Regarding the materials, it can be said that vernacular and recycled materials are more suitable for simple forms; industrial materials can also be used in this case. In the second case, we consider the dimensions of the units; in this case, the

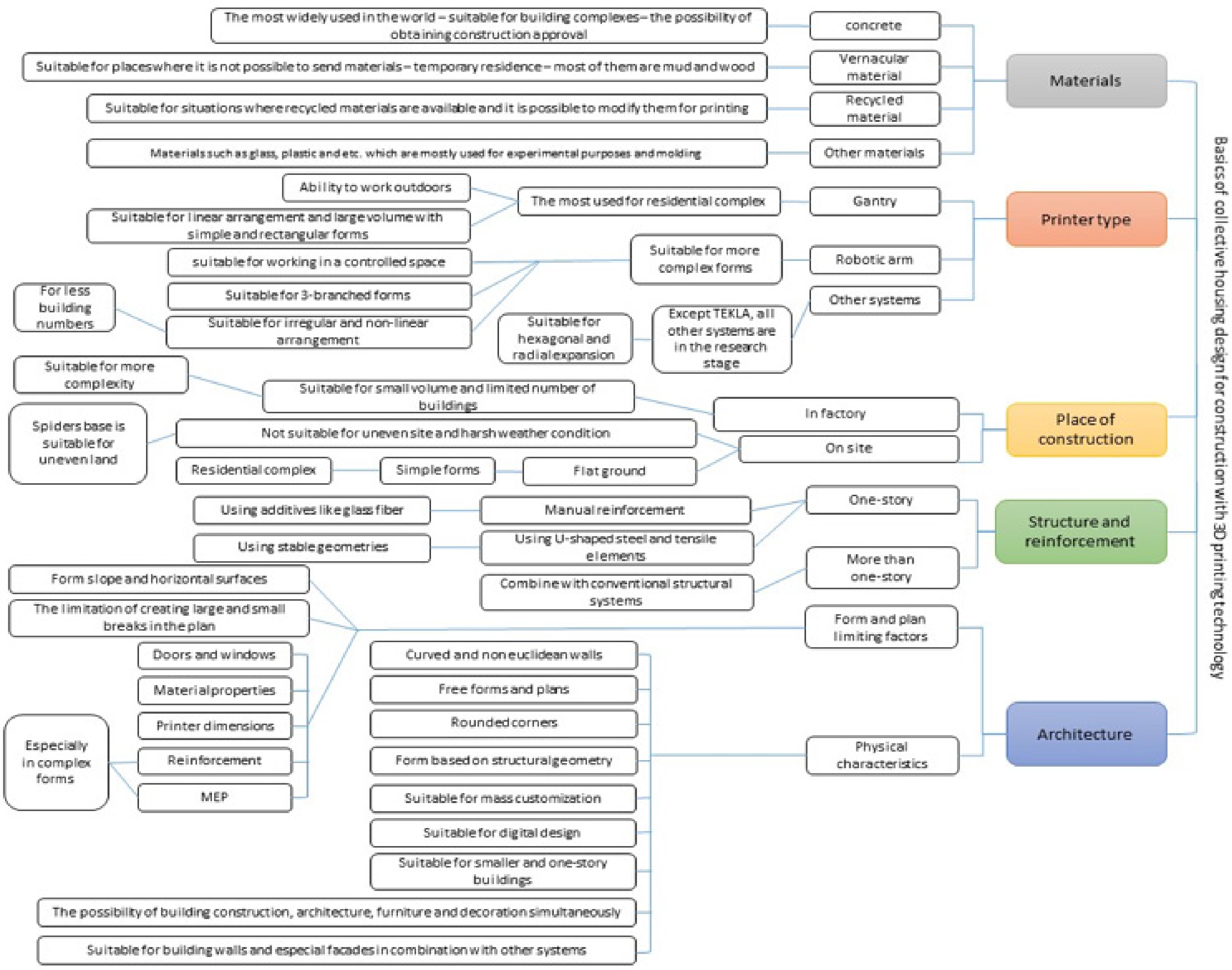

Fig 11: diagram of the basic design of housing architecture made with a 3D printer

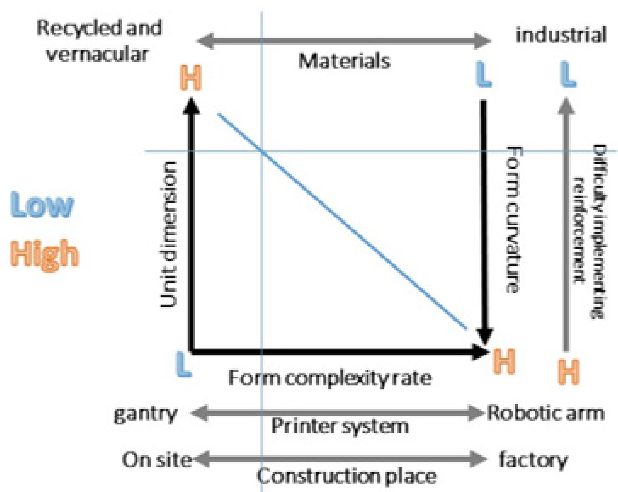

Fig 12. Decision matrix for building housing with 3D printing in different conditions

complexity and curvature of the form can be greater. In this case, the difficulty of implementing the reinforcement will increase. Industrial materials must be used, and considering the accuracy of printing with a robotic arm printer is more, this printer is recommended. Finally, construction in the factory is recommended due to the small dimensions and the need for more controlled conditions for complex forms and robotic arm printers.

CONCLUSION

The purpose of this article is to provide a comprehensive understanding of the design aspects of 3D printed buildings to increase designers' awareness to reduce errors in the design and construction process with a 3D printer, which is presented in the form of a conceptual framework diagram and matrix. To find related features, we have divided them into five categories: structure, materials, type of printer, construction site, and finally, architectural features; in the selected articles, we have looked for the cases and features of each category to increase the awareness of designers in this field. In the field of materials, it should be said that concrete is the most widely used material for housing construction with a 3D printer, and by making arrangements even in Iran, it is possible to obtain building permissions according to the building codes. In the field of printer systems, we have two of the most used systems, and more than 90% of the construction of structures is done with these two systems. The gantry system is more useful and suitable for large volumes and simple and rectangular forms, and the robotic arm system is suitable for more complex forms with limited construction volume.

Regarding the construction site, it should be mentioned that on-site construction with a gantry printer is more suitable for residential complexes, and for complex forms and limited construction, constructing in the factory is recommended. The structure's lack of tensile strength of concrete can be compensated by manually adding steel elements and reinforcing additives to concrete. In architecture, we have two categories of physical features and limiting factors. Limiting factors include restrictions on the angle of inclination of the forms, printer dimensions, reinforcement, and implementation of the facilities. The physical features include curved walls and free geometric forms, which are suitable for implementing buildings with computational design and limited dimensions and floors. If more stories are needed, they can be combined with other systems. Finally, according to the existing technology, it can be said that it alone is suitable for constructing a small one-story house with concrete and manually reinforced glass fibers with curved forms and geometry and a free plan resulting from a digital design. If combined with structural systems and conventional roofs, the number of floors can be increased, and the formal applications of this technology can be used more.

AUTHOR CONTRIBUTIONS

M.Rezazadeh designed the study, performed the literature review, collected initial data, analyzed and interpreted the data, and prepared the manuscript text and edition. H. Mazaherian and M.R. Matini Contributed to the research conceptual framework, controlled tasks, and provided good advice throughout the paper; they supervised the whole work and led the research in general. All authors have read and approved the final manuscript.

CONFLICT OF INTERESt

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the authors have witnessed ethical issues, including plagiarism, informed consent, misconduct, data fabrication or falsification, double publication and/or submission, and redundancy.

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