Classification of Robotic 3D Printers in the AEC Industry

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Abstract –
Three-dimensional (3D) printing is a branch of additive manufacturing (AM) that works by slicing a 3D computer-aided design (CAD) model into 2D layers and sequentially printing each layer additively until the entire object is obtained. There has been a growing interest in 3D printing in the architecture, engineering, and construction (AEC) industry because of its ability to lower costs, reduce waste, and simplify the supply chain. Due to the inherent nature of this technology, it requires a synergistic effort among experts in different disciplines such as architecture, material science, structural design, and robotics, to name a few. Previous studies have focused on developing, exploring, and investigating the architectural, materials, and structural aspects. However, the robotic technology aspect received relatively less attention. Thus, the objective of this study is to critically review the existing 3D printing robotic systems in the AEC industry and explicitly categorize them. At first, the literature related to 3D printing robotic systems in the AEC industry was studied, and the subjects which have not been discussed extensively were identified. Then, the gaps in the existing state of the art were identified, and lastly, a classification method was developed and discussed. To obtain the classification of the existing construction 3D printing robotic systems, five parameters were highlighted, namely fabrication place, fabrication type, materials used, 3D printer type, and 3D printing technology. In addition, the obtained classification was based on exploring the combinations of these parameters and their variations for existing applications in the AEC industry. By selecting the material that will be used, the application type, and other structural details, the printer details will be provided based on the developed classifications. The resulting classification could greatly assist and guide stakeholders' efforts to better understand and adopt 3D printing in current and future projects.

Keywords –
3D printer; robotics; classification; AEC industry.

1 Introduction

Three-dimensional (3D) printing is a method that has been highlighted in various fields and industries. From biology to engineering, 3D printing helps provide an automated method to build complex geometric shapes with the least amount of human intervention.

In the AEC industry, the adaptation of additive manufacturing started in 1998 by Khoshnevis [1]. Since then, creating and testing new materials, configurations of 3D printers, unique structural systems, and new application solutions were the new focus areas in the era of 3D printing [2].

Recently, the construction of 3D printing has evolved from an architect's modeling tool to produce a large-scale structure, especially after constructing the world's first 3D printing house (Canal House) in Amsterdam in March 2014 [3]. This is also evident from the spike in research related to 3D printing in the last few years [4,5]. The observed spike is potentially because 3D printing provides many advantages compared to conventional methods, including fewer chances of human errors, time and cost-saving and less wasted material in the whole building process [6]. Furthermore, 3D printing can also provide a reduction in work-related injuries as well [4]. As much as 3D printing showed many promising improvements to the current state of construction globally, more research is needed to improve the quality and the capability of the already existing systems.

Due to the variety of materials used in 3D printing, the scale of printing, and the purpose, different types of 3D printing robotic systems were developed. There are several parameters that distinguish one robotic system from another. The most important ones are fabrication place, fabrication type, materials used, 3D printer type, 3D printing technology, and 3D printing method. To select the appropriate 3D printing robotic systems, the right parameters should be selected. To assist 3D printing users in selecting the appropriate system for their application, this study provides a classification of 3D printing robotic systems based on existing applications in the AEC industry.

2 Literature review

Although conventional construction methods have remained relatively unchanged for decades, the new technology, 3D printing, guaranteed the capability of being an effective way to increase the project efficiency and profitability and having positive environmental impacts [6]. For those reasons and the increasing number of applications, 3D printing is receiving attention from researchers and practitioners in the last few years.

Many studies have focused on creating different structures, especially large-scale ones, enhancing their properties, and studying their printability and structural capacity. The study by Pessoa et al. [7] presented a review of the 3D printing application in the construction industry. The study concluded that 3D printing is still in an initial stage in the AEC industry. As mentioned in their study, a collaboration between the private sector and research groups counted as an essential step for developing full-scale solutions for 3D printing. Some of the examples in their study included that kind of close collaboration across the world. Another study developed by El-Sayegh et al. [4] provided a systematic review of 3D printing in the construction industry. Their research discussed and evaluated the different 3D printing techniques. It was focused on the 3D printing benefits, challenges, and risks and concluded that before confirming that 3D printing can become a viable solution in the construction industry, several challenges still need to be addressed.

Some review studies focused on a certain type of material, such as Mohan et al. [8], which focused on reviewing the material behavior spanning from the early age to long-term performance for extrusion-based concrete 3D printing. The study presented and discussed the printability and the structural capacity of the Extrusion-based 3D printing with concrete material. Another review paper by Ma et al. [9] focused on reviewing the existing 3D printing technologies of cementitious materials currently used. The three latest development of largescale 3D printing systems were summarized, and their relationships and limiting factors were identified. The study was concentrated on the printability and the structural capacity of each technology. On the other hand, Zhou et al. [10] focused on the 3D printing of polymer materials and reviewed the printability of this type of material. The study investigated the limitations of using polymer materials in construction 3D printing. In addition, Buchanan and Gardner [11] reviewed metal 3D printing techniques in construction. The printability and the structural capacity were discussed in detail. Their research was focused on the methods, the application, the challenges, and the opportunities of metal 3D printing.

In 2018, Ozturk [12] provided a review of different applications of 3D printing technology in industries other than the construction industry to examine their attempts in the construction industry and provided an outlook on possible future application areas.

This resulted in the identification and classification of the state-of-the-art 3D printing technological developments for various industries and made projections on the possible adaptation areas in the construction industry.

Kidwell [6] analyzed progressive 3D printing companies that have effectively employed 3D printing technology on a full scale. This research aimed to examine the current uses of 3D printing technologies in construction and then highlight the best practices and applications while considering the technology's existing limitations and creating an outline for these applications. The study was focused on the type of materials, printability, and structural capacity. Duballet et al. [13] conducted a study on building systems related to concrete extrusion-based 3D printing techniques. The study highlighted specific parameters such as concerning scale, environment, support, and assembly strategies and proposed a notation system to classifying building systems depending on concrete 3D printing.

In 2016, Rogers et al. [14] Provided a research agenda for future studies on the impact of 3D printing services on supply chains by identifying types of 3D printing services available today and identifying the potential impacts of these services. However, this study did not provide any details regarding printability and structural capacity. Perkins and Skitmore [3] investigated the state of the art construction 3D printing practices and their future potential based on the review of relevant literature. In addition, the technology could be applied to construct buildings far more quickly and at a much lower cost. Their research described in detail the three main 3D printing methods used for cementitious materials: contour crafting, concrete printing, and D-shape. It concluded that approximately 30% of waste could be reduced by 3D printing, which makes it a very attractive proposition for construction.

The literature review thus confirms that as 3D printing is still in its infancy in the AEC industry, research is still focused on the materials used, printability, and structural capabilities. The research gaps found after reviewing the literature are:

1. Most of the studies were developed to review 3D printing based on the materials used and printer methods, the studies that review general 3D printing in construction are very few.
2. Most of the studies provide a 3D printing classification for a certain technology or technique; none of the studies provided a general 3D printing classification.

3 Research aim and objectives

This study will provide a classification of the existing 3D printing robotic systems in the ACE industry, focusing on the 3D printer's details and different applications. The following objectives will lead to achieving the mentioned aim of this study:

1. To explore the existing 3D printing robotic systems in the ACE industry.
2. To identify different applications of the analyzed 3D robotic systems.
3. To develop a classification of the 3D printing robotic systems.

The proposed classification will assist the building designers, and construction professionals choose the appropriate 3D printing robotic system(s) for their particular context and application.

4 Methodology

To achieve the abovementioned objectives, the following methodology is employed. First, a systematic literature review was done to collect the 3D printing robotic systems' details and their different applications. The literature was reviewed to collect the details of different 3D printing robotic systems used in construction. The collection process focused on the methods used in 3D printing and other parameters such as the material used, the area of the structure printed, fabrication place, fabrication type, and 3D printing technology. Second, application details were collected to show the 3D printing robotic system's capability. Lastly, based on the collected data, a classification was developed. The above mentioned methodology is shown in the form of a flowchart in Figure 1.

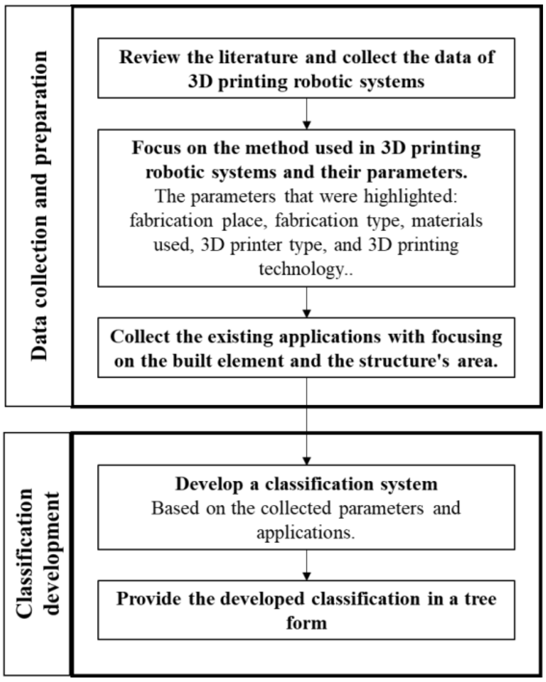

Figure 1: Steps involved in the proposed research methodology to develop a construction 3D printing robotic systems classification

4.1 Data Collection and Preparation

There are a variety of 3D printing robotic systems, methods, and types used in the construction industry. It is very important to understand every aspect of these systems, methods, and types before choosing the right system for their context or application. Lack of such an understanding will not only lead to choosing the wrong method, system or type but also might have time, cost, and resource implications on projects. Therefore, to comprehensively understand and map these, this research was focused on collecting different parameters that may affect the selection of the proper robotic system, such as the materials used, fabrication place, fabrication type, 3D printing technology, and 3D printing method. Although this is not an exhaustive list of parameters, these are some of the most significant factors impacting the selection of the right 3D printing robotic system(s) as per the authors' and industry professionals' experience.

After collecting the existing 3D printing robotic systems in the AEC industry and their different applications, the following are the details of each parameter.

- Material used:

The existing materials used for 3D printing in the AEC industry are polymer, cementitious, and metal materials.

- Fabrication place:

According to the literature, it was found that the 3D printing structure can be fabricated either on-site or off-site where the most application was constructed.

- Fabrication type:

Based on different applications, it was found that there are two different fabrication types used in 3D printing, Additive Fabrication (AF), where the object or element is built by layering materials on top of each other, and Formative Fabrication (FF), where heat and pressure are used to form the material into the desired shape.

- 3D printing technology

To meet the requirements of different materials used in 3D printing, various technologies have been developed. Based on [11] and according to ASTM Standard F2792, seven printing technologies have been developed for 3D printing until now [16]. The first technology is the Powder Bed Fusion (PBF), which is melting and fusing the powder material using a laser or electron beam. All PBF processes require that the powder material should be spread over previous layers. The second technology is Vat Photopolymerization, in which a vat of liquid photopolymer resin is used to construct the model layer by layer. In addition, it uses liquid to form objects. Unlike the PBF technology, during the build phase, there is no structural support from the material itself, where the support is given from the unbound material. The third technology is Material Jetting, in which the material is jetted into the platform, then it solidifies. In this process, layer-by-layer, the material is extruded through a nozzle that moves horizontally across a platform to deposit material where needed. The fourth one is Material Extrusion which is the most commonly used technique. In this technology, by depositing the material through a nozzle layer by layer, in some methods, such as in the Fused Deposition Modeling (FDM) method, the material is heated. The nozzle moves horizontally, and after depositing a new layer, the platform moves vertically. The fifth technology is called Binder Jetting, which uses two materials to build the desired structure, namely a powder-based material and a binder. Typically, the binder, which acts as an adhesive between powder layers, is liquid, while the build material is powder. In a horizontal motion, a print head alternately deposits layers of build materials and binding materials, and when a layer of an object is printed, it will be lowered on its build platform. The sixth is Energy Deposition. In this technology, a nozzle is installed on a robotic arm with several axes, where melted material is deposited on the desired surface, where it solidifies. Although material extrusion is similar in principle to this process, in this technology, the nozzle can move in more than one direction. The seventh and last technology is Sheet lamination. This technology uses metal ribbons or sheets welded together with ultrasonic energy. During the welding process, computer numerical control (CNC) machining and removal of unbound metal are required. Metals such as aluminum, copper, stainless steel, and titanium are used in this technology [29].

- 3D printing method

Since the technology can be implemented in different techniques, different printing methods were developed for each technology. Based on existing applications for polymer materials, four different methods are used: Fused Deposition Modeling (FDM), Digital Projection Lithography (DLP), Paste Dispenser, and FreeFAB. For cementitious materials, there are five different methods: Contour Crafting, Concrete printing, D-Shape, Fused Deposition Modeling (FDM), and Fused material powder. Lastly, for metal materials, three different methods exist. These methods are Selective Laser Melting (SLM), Ultrasonic Additive Manufacturing (UAM), and Direct Energy Deposition (DED) [10].

This study focused on collecting the existing printing methods for each application and the details of each parameter to demonstrate the ability of each printer. After collecting all these details, the classification was developed and summarized in the next section.

4.2 Classification Development

The classification with nine different levels was developed based on the collected data. Since the objective was to develop a classification for an AEC professional (or user) with minimal to no prior expertise in construction 3D printing, the classification levels were broken down into two parts: user selection and 3D printer details (Figure 2). Since the entire classification was too big, to better visualize it, it is segregated based on the type of material. Each of the different levels in the classification for each of the materials is shown in Figures 3 and 4. Each of the levels and components involved in the classification was already described in the methodology. To make the classification crisp and easy to view, abbreviations were used for different levels and components.

In order to select the appropriate 3D printing robotic system based on the developed classification, the user should select the type of material that they intend to use, decide if just an element or the whole structure will be built, the area of the structure, and similar application of what he/she wants to build. Based on their selection, the printer details (i.e., the printing method orienting technology, fabrication type, printer type, and fabrication place) are provided in the lower levels of the classification. It was mentioned before that the classification was built based on the previous application. The resulting classification for each material is presented in Figure 3 (for cementitious) and Figure 4 (for polymers and metals).

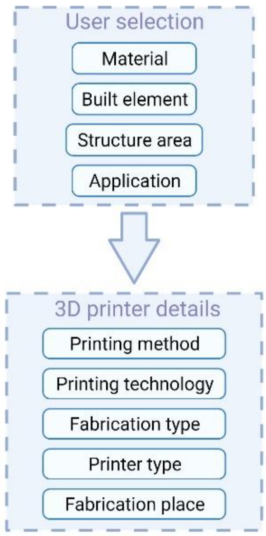

Figure 2: Classification levels (created using biorender.com)

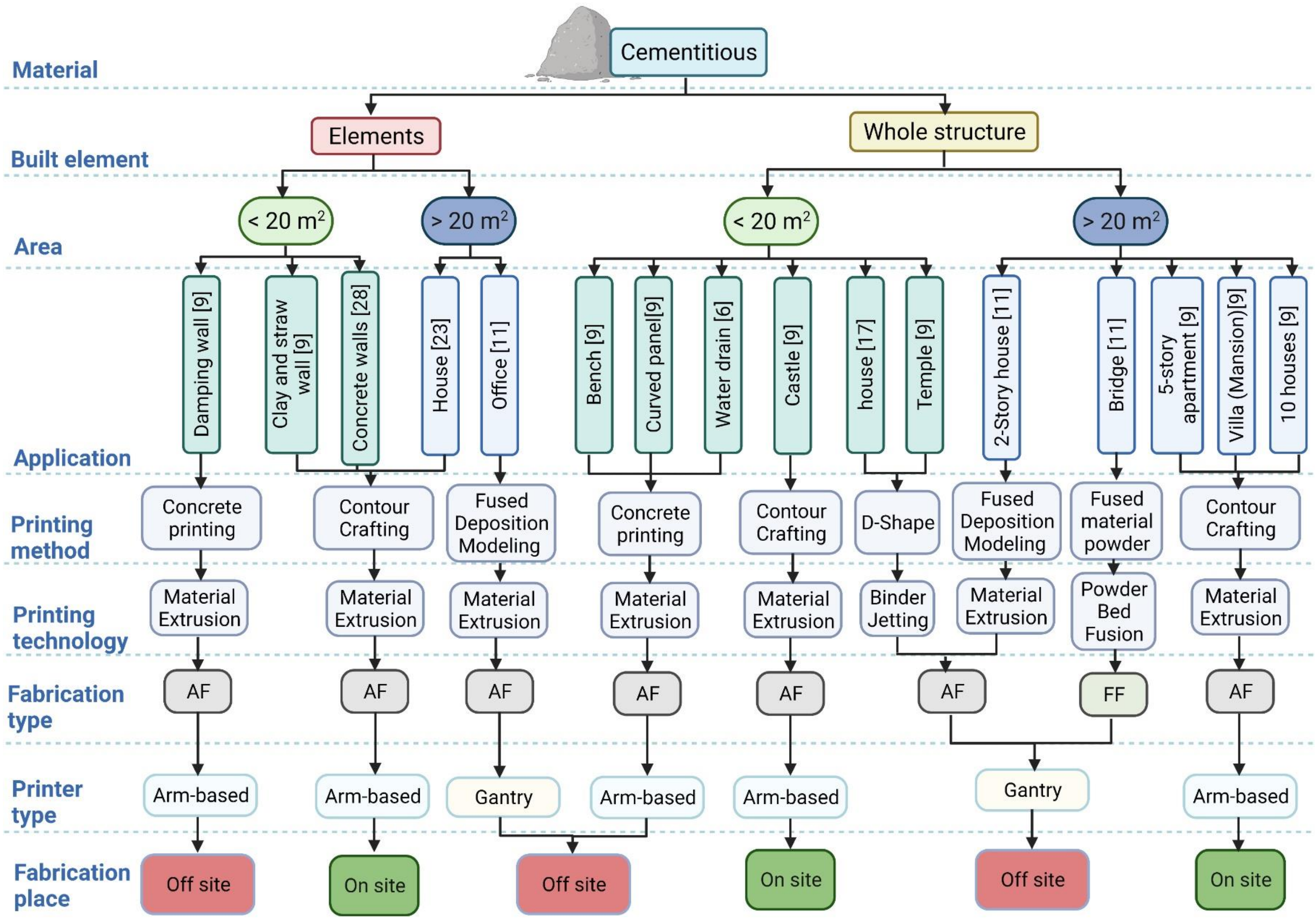

Figure 3: 3D printing robotic systems' classification of cementitious materials (created using biorender.com)

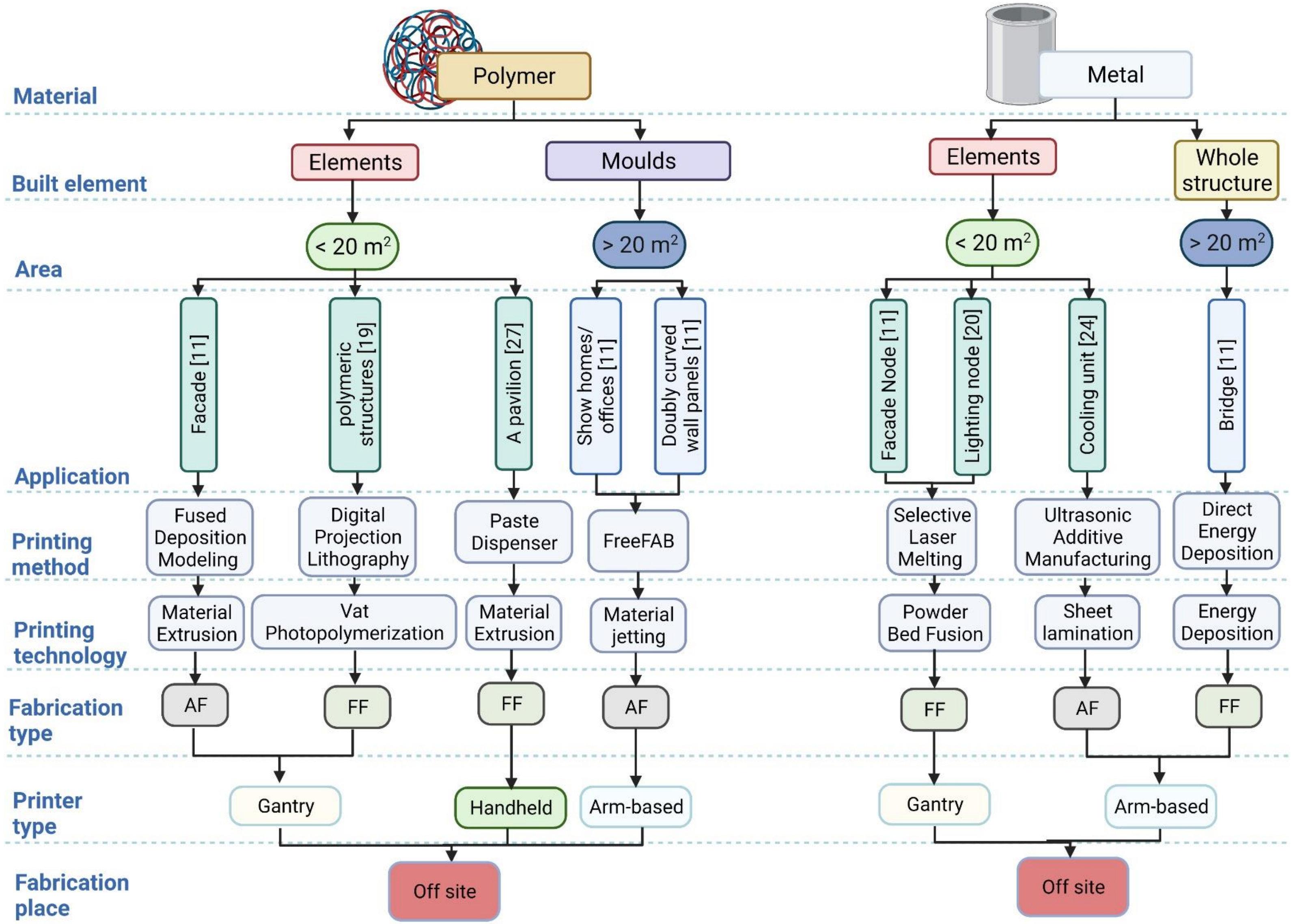

Figure 4: 3D printing robotic systems’ classification of polymer and metal materials (created using biorender.com)

5 Results and discussion

In the resulting classification, 16 existing applications were collected for cementitious materials, while only five and four applications were collected for polymers and metals, respectively. Therefore, the most popular material used in 3D printing in the AEC industry is cementitious material. The use of polymer and metal materials is limited, especially on large-scale structures.

However, polymer additive manufacturing is the most common method because of its low cost and widespread equipment availability. Moreover, the developed classification showed that most 3D printed structures were printed off-site, and the most popular printer type is the arm-based. In addition, all the onsite implementations are arm-based using cementitious materials.

The presented classification was developed using the existing applications with full details of the nine levels. Some of the collected methods and applications were excluded because of the limited information (e.g., no application was found for the Selective Laser Sintering (SLS) method used for polymer materials, so this method was excluded. Also, the polymeric structures in [19] were excluded because it has no structural details). The developed classification can and should be updated when new applications surface.

Most of the studies proved that the AEC industry is trying to Investigate new ways for improving project efficiency, and using 3D printing can reduce time and cost and improve quality and labor safety. The developed classification can support the decision-making process to select the appropriate 3D printing systems in future projects.

6 Summary and Conclusions

This research developed a classification of the existing 3D printing robotic systems in the AEC industry. The literature was reviewed to demonstrate the current status of real-world implementation in the AEC industry. It was found that 3D printing is still in an early stage in the AEC industry. After reviewing the literature, data of different 3D printing robotic systems were collected. Then, different existing applications for each system were collected with providing its details to determine the capability of the system. The collection procedure focused on data from different 3D printing robotic systems based on parameters such as the materials used, fabrication place, fabrication type, 3D printing technology, and 3D printing method. There were three types of materials used in 3D printing in constructions, namely Polymer, Cementitious, and Metal. The fabrication place can be either on-site or off-site. There were two different fabrication types used in 3D printing: Additive Fabrication and Formative Fabrication. In addition, there were seven different printing technologies: Powder Bed Fusion, Vat Photopolymerization, Material Jetting, Material Extrusion Binder Jetting, Energy Deposition, and Sheet lamination. After collecting all the needed data, a classification was developed, and the use of the classification was discussed. Due to the big size of the classification, it has been divided into smaller clusters based on the type of material. For each material, the classification represents the existing 3D printing robotic system's details. When new applications emerge, the classification should be updated. The developed classifications showed that the most used material in 3D printing in the AEC industry is cementitious. Although polymers are the most common material used in 3D printing in different industries, it is limited in AEC industry. The right parameters should be selected in order to determine the appropriate 3D printing robotic systems. In this instance, the developed classification is used. Based on selecting the material, the similar application, and other details from the first four classification levels, the 3D printing robotic system's details are obtained. The resulting classification could greatly assist and guide stakeholders' efforts to better understand and adopt 3D printing in current and future AEC projects.

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