Architectural Design for Additive Manufacturing Construction: Lesson Learned from Design for Additive Manufacturing

Vikrom Laovisutthichai [1]✉

Email: Vikrom@connect.hku.hk

Weisheng Lu [1]

Fan Xue [1]

[1] Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, Hong Kong SAR

Abstract

Additive Manufacturing (AM) is widely studied in many fields, including aeronautics, automotive, medicine, and construction. Some researchers expect AM to benefit construction practice in terms of reducing waste, alleviating time overrun, and breaking design limitations. With the high-level customizability of AM construction, designers are less constrained, e.g., by design standardization, in designing bio-inspired forms, natural curves, and uniqueness in construction projects. Nevertheless, AM technology also faces challenges, such as high printing cost, inability to print, and weak structure during a layer-by-layer printing process. Design for Additive Manufacturing (DfAM) has, therefore, been proposed for the construction industry. This paper revisits the lessons learned from the problems and the DfAM solutions to real-life cases. First, due to AM's capability to construct without casting molds, self-support structure, e.g., plate and shell structure, should be included in the designs. Secondly, according to DfAM guidelines, a large amount of temporary support structure, overhang, thin feature, and flat surface are among the major factors affecting the efficiency of AM. In comparison, there are several architectural elements, such as long-span structure, cantilever part, thin wall, and flat roof can be the barriers to AM in construction. In order to promote the application of AM in construction and achieve higher efficiency, new DfAM guidelines for the construction sector are demanded.

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Keywords

3D printing
Design for X
Design for additive manufacturing
Construction automation
Architectural design

1. Introduction

3D printing technology, also known as Additive Manufacturing (AM), has been studied in a wide-range of industries, including manufacturing, medicine, aeronautics, automotive, as well as construction. With its abilities to customize individual requirements, reduce waste from the production process, and produce eccentric forms, many industries see it as an opportunity to achieve a high level of customer satisfaction with a reasonable budget [1, 2]. For instance, in the dental industry, layered fabrication innovation has been introduced to produce dental restoration and artificial organ [3]. The recent study also mentions that when this fabrication method is fully developed, the second revolution of manufacturing will occur [4].

The possibility and feasibility of AM in construction have also been analyzed by researchers, as the industry currently experiences with several challenges, a shortage of construction workers, labor costs, waste management and site safety incidents [5, 6]. From the recent study, the benefits of adopting AM in construction are a customization production, design flexibility, efficient material usage, raise construction performance, shorten time, decreasing the number of labors, saving financial cost, and reducing environmental impacts [7]. Several studies agree that AM will enhance construction productivity, lift users' satisfactory, and bring the industry closer to a fully automated procedure in the future [5, 7, 8].

However, AM is not free from criticism. The implementation of the technology in manufacturing also faces many issues, unsatisfactory productivity, unable to print, high cost, and limited material alternatives [2, 9]. The application of AM in real-life construction is also questioned by many researchers, due to the differences between manufacturing and construction [5, 7, 8]. A plethora of research has proposed a new design approach, Design for Additive Manufacturing (DfAM), also known as Design for Rapid Manufacturing, to solve manufacturing issues and increase the productivity in AM construction [9, 10, 11, 12]. According to the previous real-life case study, the application of DfAM in the design process for manufacturing can prevent printing problems and boost its efficiency. Moreover, the guideline can be advantageous for new users to avoid common mistake, and comprehend the principle of AM [9, 13].

Therefore, a lesson learned from DfAM is currently demanded in order to support the applications of the new manufacturing concept for the construction industry in the future. The remainder of this paper consists of four sections. The following part is to review AM and design criteria from DfAM concept. Architectural design elements, which have possibilities to be advantages and barriers to AM construction, are analyzed in the Sect. 3. In the final stage, a conclusion and discussion are drawn.

2. Literature Review

2.1. Additive Manufacturing and 3D Printing

The definition of Additive Manufacturing (AM), provided by the American Society for Testing and Materials (ASTM), is “a process of joining materials to make objects from 3D model data, usually layer upon layer” [14]. 3D printing is an automated process of making three-dimensional object under AM concept [15]. Unlike the former production concepts, subtractive or formative process, AM produces the product by adding layer instead of removing some materials [16].

In general, the process of AM can be divided into four stages, which are digital model creation, slicing, printing, and post-production [2]. **(1) Digital model creation**: Starting from computer-aided design (CAD), designers use the modeling software to generate 3D digital model. **(2) Slicing**: Since the manufacturing method of AM is adding layer after layer, the 3D digital model will be sliced horizontally before the printing stage, based on material’s properties and printer’s specifications. **(3) Printing**: AM Machine prints 3D model directly from the digital file. From the seamless production process, it can resolve some misunderstandings between designers and manufacturers. **(4) Post-production**: This stage includes material removal, smoothening, painting, polishing, consolidating with other parts, etc. The AM process can be varied, owing to the alternatives of materials and designs [16, 17].

The advantages of using AM in the manufacturing industry include, inter alia:

High customizability: A variety of designs can be produced by one machine, since there are no requirements for changing casting mold, temporary supporting structure, or equipment.

Simplified process: Unlike the former manufacturing process, design and production must be done separately, the production of AM can be started immediately.

Shorten time: Owing to the borderless between design and manufacturing stage, prototype can be printed by designers and computer software. It makes learnings by trial and error method, design-build-fail-redesign-rebuild, faster than before.

Cost-effectiveness: By the simplicity of the production process, the time, cost, and quality are more predictable and manageable. Moreover, it does not have tools and equipment costs.

Reduced waste generation: While subtractive manufacturing causes industrial waste resulting from removing unwanted parts from a solid form, AM produces as necessary by adding layer instead of cutting out.

Less manpower requirement: Due to the fully automated production, the process needs fewer labors than conventional methods [2, 13, 18, 19].

2.2. Additive Manufacturing in the Construction Industry

As the construction industry face challenges, e.g., a high demand for construction projects, escalating in costs, unsatisfactory performance, site incidents, manpower shortage, decreasing productivity, and lack of creativity, AM has been introduced in order to resolve issues and revitalize the industry [6]. However, there is a limited number of AM in construction cases, and the research are still in the initial stage [5].

Several research and cases have been done to study the possibility and feasibility of AM in the industry. Nowadays, there are three well-known construction systems based on AM concept, which are contour crafting, D-shape, and concrete printing. All systems produce by adding layer-by-layer, while the differences among them are machine specifications and materials. Researchers agree that with fully developed system, AM concept can be successful in construction, as a tool to make unique and nonrepetitive products [19, 20].

One of the recent developments is created by WinSun, a Chinese company based in Jiangsu province. They used AM technology to print building components for 5-storey apartment block before assembling them on site. The building design mostly consist of straight lines and box spaces. The company claimed that either traditional architectural style or highly detailed 3D models can be built with their AM technology. Moreover, it can be a solution for most of conventional construction issues [1, 21].

2.3. Design for Additive Manufacturing (DfAM)

According to the study, it highlights that conventional design methods are not appropriate for AM. During the design process, designers are required to shift their methodology and decision making from traditional subtractive approaches. In order to improve the AM performance, many ideas have been proposed, including Design for Additive Manufacturing (DfAM) [22].

From the research on DfAM, the example of design criteria for AM production are as follows. **(1) Structural optimization**: Since the cost of 3DP is variable corresponds to the amount of material, the optimization of a structure without changing the design is needed to reduce manufacturing cost and time**. (2) Model strength**: Inability to print, deformation, and structure failure are three significant problems, resulting from weak structural systems. Designers, therefore, should take materials properties, machine specifications, and structural performance into account. **(3) Model stability**: Products are affected by various forces during and after production process. For risk prevention, users should verify that the model is in the balance state. **(4) Printing orientation**: Many times, critical printing issues, can be resolved without redesign by changing orientation. The techniques, e.g., model rotation, shifting, turning over, flipping, are used to avoid overhang, and reduce temporary supporting structure in AM. **(5) Temporary supports and unsupported features**: Temporary supports and unsupported features are crucial factors affecting the manufacturing productivity. With a lot of temporary supports, the model wastes more time and materials, while unsupported features can cause structural failures in production stage. As a consequence, these should be carefully considered in the design process [2, 17, 22].

3. Analysis

3.1. The Application of Additive Manufacturing in Architectural Design

Although AM provides opportunities to design unique products, it still experiences with some challenges related to printability and cost efficiency [11]. In order to support AM in the industry, an appropriate design is among the keys to success. From the characteristics of AM, the method is printing layer by layer without casting molds or temporary support structure. It is faster, safer, and less material waste than other construction methods. Thus, building structure, requiring casting molds and supports during the process, e.g., column-beam structure, should be avoided. The design, which is appropriate to AM, should be self-supported (Table 1).

Table 1

Construction methods and opportunities in architectural design

Construction methods	Opportunities in architectural design
Conventional in-situ construction (require molds and temporary support)	Column-beam structure (require molds and temporary support for casting concrete)
Precast construction (require molds in manufacturing plant)	Load bearing wall structure with steel reinforcement (require molds for casting concrete in production line)
Additive manufacturing construction (construction without casting molds)	Self-supported structures, e.g., vault, plate, and shell s(not require casting molds)

In architectural design, vault, plate, and shell are the examples of self-supported structures, which can be applied for AM in construction. Sydney Opera House and TWA terminal are two examples of shell structure buildings. To construct plate and shell structures in a conventional construction, plenty of casting molds need to be prepared in the pre-construction stage. It badly drops the construction efficiency; hence, a limited number of plate and shell structures have been constructed in the past. With its capability of producing self-supported structure without molds, AM is likely to be a proper construction method for plate and shell structures (Figs. 1 and 2).

Fig. 1

Shell structure at Sydney opera house [23]

Fig. 2

Shell structure at TWA terminal [24]

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3.2. The Comparison of DfAM Design Checklist and Architectural Elements

In order to make the AM design guidelines useful, Joran W. Booth has reviewed and summarized into one worksheet for all users in 2015, especially for novice and intermittent designers, to evaluate their designs by themselves before printing layers [9]. It can be seen from the worksheet that model complexity is not the difficulty of the printing process. On the other hand, several conditions affecting the risk of printing failures are designs with a large amount of supporting structure, overhang, thin features, corner without support, and huge flat area [9, 23, 24]. Comparing to an architectural design, some commonly used elements are likely to be like these conditions. They have the potential to be a barrier to AM construction, as seen in Table 2.

Table 2

The comparison between manufacturing and architectural design elements

Designs should be avoided for additive manufacturing	Problems can be found in additive manufacturing	Architectural elements likely to be barriers
Temporary supporting structure	Need the removal process after production	Long-span structure, cantilever structure, and openings
Overhang and unsupported feature	Inability to print, structural failure, or product defect	Long-span structure, cantilever structure, and openings
Thin features	Easily breaking during and after manufacturing	Thin wall and canopy
Corners without chamfers, or fillets	Need more process and longer manufacturing time	Sharp edges and corners
Functionality	Product unable to handle heavy duty works	Door hinge, knob, handle, etc.
Large flat area	Inability to print, structural failure, and product defect	Huge flat roof, and floor

Temporary supporting structure: The design with temporary supporting structure in AM requires post-production process to remove manually, as shown in Fig. 3. It wastes material, prolongs manufacturing time, and increases the number of labors. Moreover, to remove temporary support, the surface could be destroyed. Column and beam structure, commonly used in the architectural field, also needs formwork frames to support and shape wet-concrete until it is self-supporting, as shown in Fig. 4. Some openings shapes also require lintel to bridge the gap before adding layer above. This causes an interruption during printing process. To enhance 3DP construction, the architectural elements, required temporary support structure during construction, needs to be reconsidered.

Fig. 3

D printing product with temporary supporting structure [25]

Fig. 4

Formwork frame for concrete casting in construction [26]

Overhang and unsupported feature: A large amount of overhang or bridge without supporting structure cause severe problems in production, including the inability to print, production defect, and structure failures, as shown in Fig. 5. Comparing to architectural elements, cantilever or wide-span structure without bracing or drop panel should also be avoided. For layer by layer printing construction, the lower layer should be able to instantly support loads from the upper layer. By applying this method, the project can reduce temporary support structure or casting mold, and save a great amount of time, cost, and labor (Fig. 6).

Fig. 5

A defect from 3D printing production without temporary supporting structure [27]

Fig. 6

Wide-span structure in architectural design [28]

Thin features: Due to the limitation of printing process and material specifications, thin features in AM are easily broken during and after production phase. In architectural design, thin wall and canopy design should be considered using other construction methods instead.

Corners without chamfers, or fillets: Because of the machine specifications, sharp corner need longer manufacturing time, otherwise the surface will be rough, as shown in Fig. 7. While in conventional construction, corner bead has been used to make wall corners sharp. By this step, more production time and materials are required (Fig. 8).

Fig. 7

A rough corner [29]

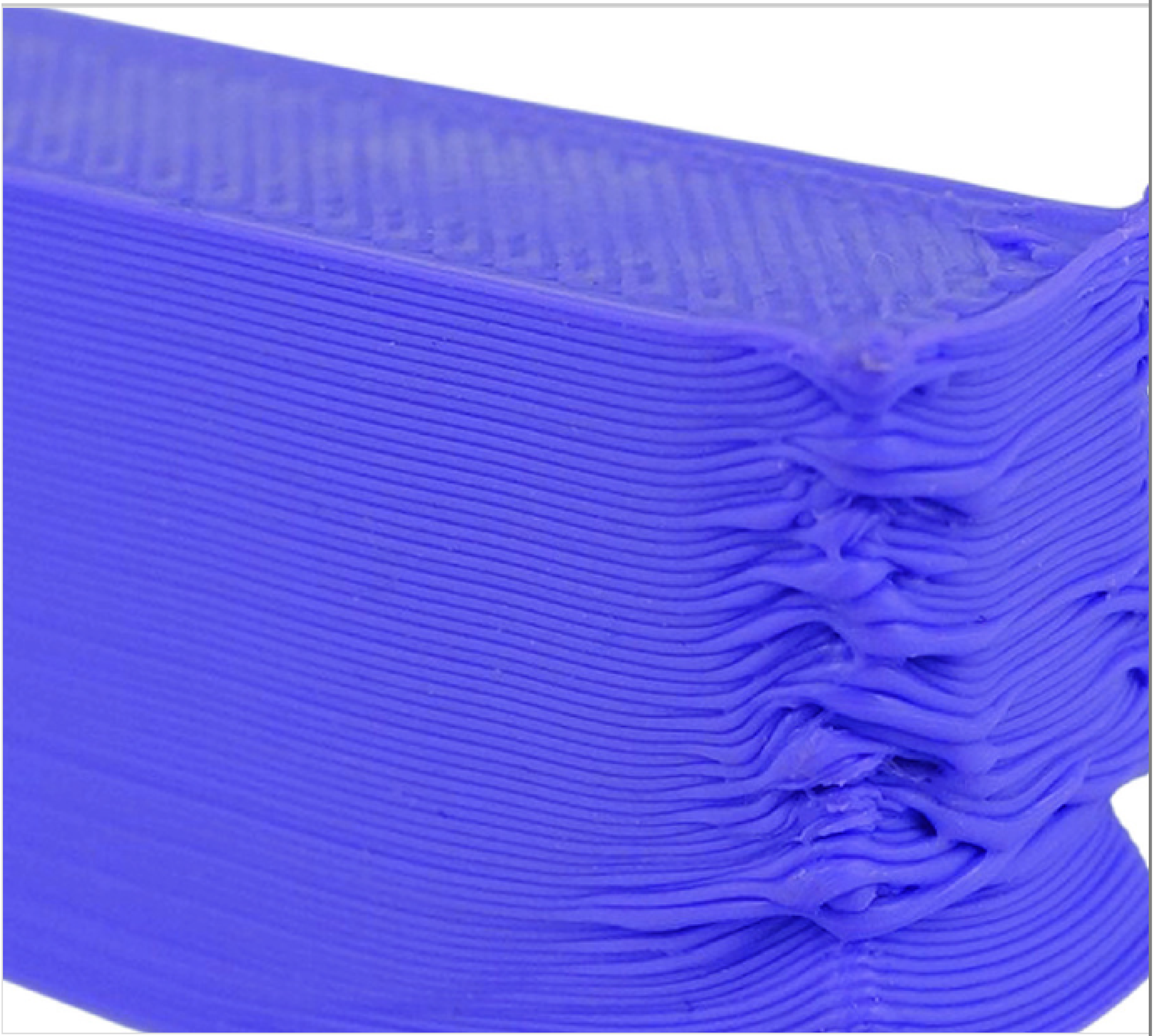
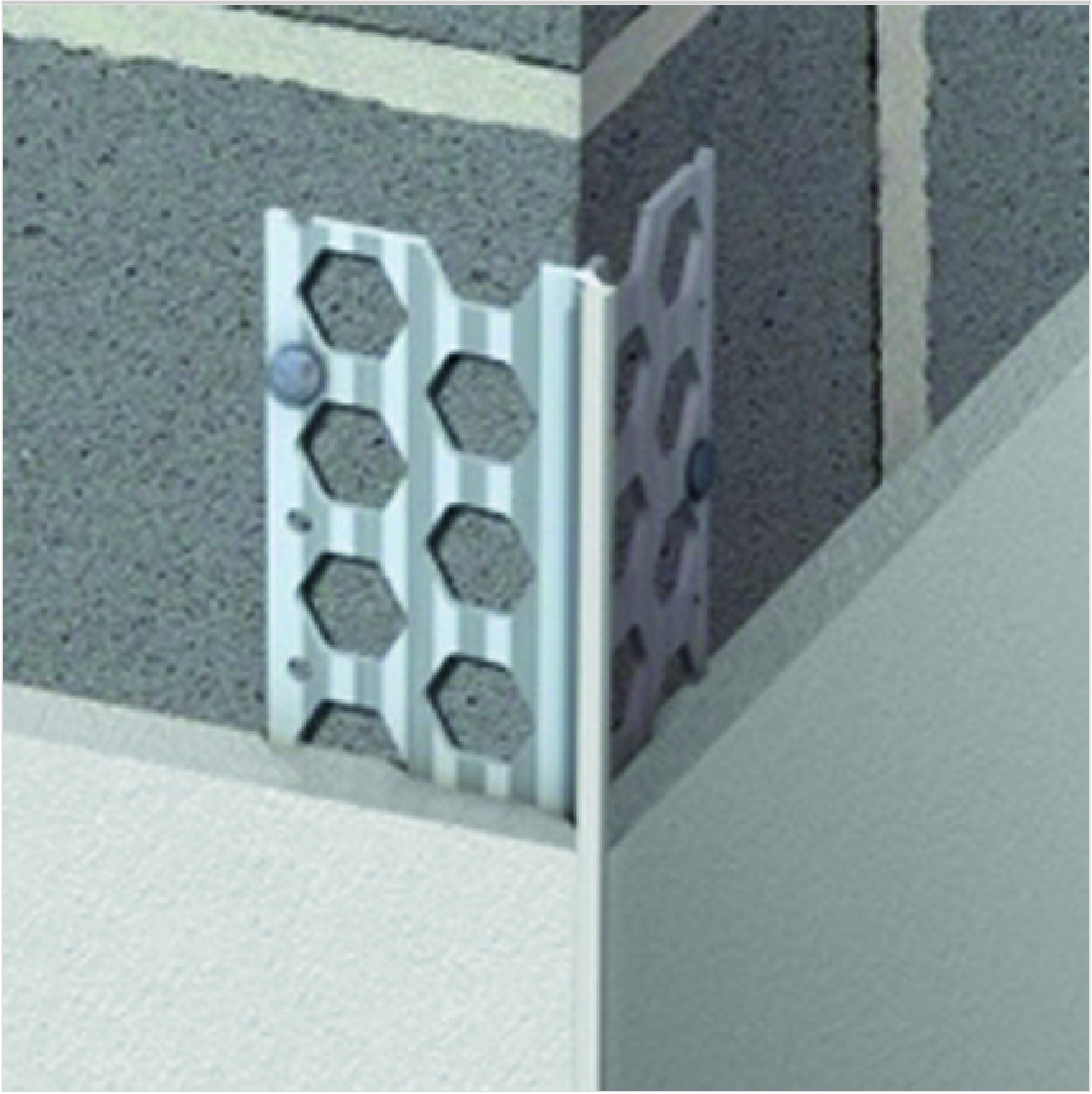


Fig. 8

Corner bead in construction [30]



Functionality: Products from AM manufacturing are capable of serving light and medium duty. In order to handle heavy duty in architecture, e.g., doors' hinge, knob, and handle, using conventional methods can make products more durable.

Large flat area: By adding line-by-line and layer-by-layer, large flat area can be constructed by printer; nevertheless, it wastes a lot of time for production. For a huge flat roof construction, it would better to consider using other technologies.

It is apparent that the capable of AM gives freedom to design a complex form and irregular shape; nonetheless, it still has its own constraints resulting from the specifications of printer and material. To achieve better efficiency, several ideas, e.g., self-supported structure, should be included into the design, while some common design elements should be avoided.

4. Conclusion and Discussion

4.1. Conclusion

With its advantages including customization, working simplification, shortening production time, and eccentric form production, Additive Manufacturing (AM) is predicted by the construction industry to be the new revolution of a production process in the future. For designers, the application of AM makes bio-inspired form, eccentric shape, and curvy line buildability for the first time. It breaks the former design constraints, box spaces and straight lines.

One of the most prominent abilities of AM is product manufacturability without casting molds. A large amount of cost, labors, and time could be saved. To advance the efficiency of AM, self-supported structure should be included in the designs. In comparison to architectural elements, there are several frequently-used self-supported structures, e.g., plate and shell structure of Sydney Opera House and TWA Terminal. Despite difficulties from casting molds preparation in conventional construction, shell structure is possible to be built efficiently in AM construction.

On the other hand, according to design for additive manufacturing (DfAM) guidelines, there are several concerns that designers should take into accounts, e.g., designs with a large amount of temporary supporting structures, overhangs, thin features, corners without support, and huge flat areas. From a comparative study, there are some architectural elements, which appear to be barriers in AM construction, such as long-span structure, cantilever part, thin wall, and flat roof. Unlike traditional design approach, the design process for AM needs to be reconsidered in order to lift its efficiency. Especially for the construction industry, the AM buildability should be a key to concern for designers.

4.2. Discussion

This paper has preliminarily reviewed some DfAM guidelines and proposed the opportunities and barriers in architectural design for AM construction. Since the research on the application of AM construction and DfAM is currently in the infant stage, reviewing and analyzing DfAM will be useful for construction sector.

Moreover, to advance the study, a number of real-life cases and empirical studies still need to be researched.

The arrival of AM technology will be beneficial for every industry to achieve higher productivity, better customers' satisfactory, safer working environment, and lower material waste. Nevertheless, this method is not the absolute solution to solve every issue. Since AM is not appropriate for every design, it is essential for stakeholders to realize the principle of each construction method and select the most appropriate solution. In order to make AM successful in the construction industry and promote understanding among users, new guidelines for AM in construction is highly demanded.

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