Review

Design for Manufacture and Assembly (DfMA) of Digital Fabrication (Dfab) and additive manufacturing (AM) in construction: A Review

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Abstract: A Design for Manufacture and Assembly (DfMA) in architectural, engineering, and construction (AEC) industry is attracting the attention of designers, practitioners, and construction project stakeholders. Digital fabrication (Dfab) and design for additive manufacturing (DfAM) practices are found apparent needs for development. The DfMA's conceptual function is to maximize the process efficiency of Dfab and AM building projects. This work reviewed 153 relevant research articles over the past few decades. The concept of DfMA and the fundamentals of DfMA in building and construction were explored. In addition, DfMA procedures associated with Dfab and DfAM, as well as its AM assembly process, were discussed. Lastly, the current machine learning research on DfMA in construction were also highlighted. Large research gaps in the DfMA for Dfab and DfAM can be filled to significantly increase operational efficiency and sustainable practices.

Keywords: design for manufacture and assembly; digital fabrication; additive manufacturing, construction, review

1. Introduction

To response to architectural and engineering needs for flexibility, complexity, high performance, intricacy, customization of material, and technology [1-4], the construction industry has to create novel techniques and technologies such as digital fabrication (Dfab) and additive manufacturing (AM) technique. Although the construction industry has been identified as a big consumer of resources and a **substantial environmental impact**, it is considered one of the inefficient manufacturing practices [5]. The automation in construction and architecture [6-8] is proposed as an alternative to costly and inefficient manufacturing practices. This digital architectural paradigm is anticipated to have a favorable impact on the built environment. As a result, the architectural profession is required to develop completely automated production forms and procedures that promote equality, sustainability, democracy, diversity, and inclusivity.

Understanding the influence of sophisticated technology on the field of architecture may direct future studies, inspire innovative design and construction techniques, and improve teaching strategies. AM technology is preferred above other Dfab technologies due to its operational potential in the architectural, engineering, and construction (AEC) sector. This approach might enable the sustainable construction of complicated building designs with less material and without the requirement for conventional formwork. AM technology may be utilized in all phases of the design process, from form-finding prototypes through the production of full-scale constructions.

AM is the process of printing multiple layers of materials on top of each other [9, 10]. Frequently, the words "additive manufacturing," "rapid prototyping," and "3D printing" are used interchangeably to refer to the process of constructing an item through the

progressive addition of material layers. ISO/ASTM 52900 [11] terms the AM as "a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies." Since the mid-1980s, as Charles Hull invented the first commercial AM printer [12, 13], this AM or 3D printing technology has been gradually evolving. Pegna [14] created the first large-scale concrete printer in the late 1990s, enabling the construction sector to adopt 3D printing. Although the creation of this technology began more than 30 years ago, its fast development began considerably later. The framework of new development shown that the number of articles on the use of 3D printing technology in the construction sector has risen over the past decade [15]. There is a rising interest in implementing and expanding this technology within the construction industry and, subsequently, throughout architecture. Recent architecture construction projects were worldwide built by large-scale AM machine, and the AM instances were displayed in Figure 1. Two methodologies of 3D printing for construction have been widely developed which are extrusion (or Fused deposition modeling; FDM) and powder-bed 3D printing cement. The concepts of both processes are exhibited in Figure 2. Numerous researchers have analyzed this technology's influence and use in the building industry [7, 8, 16-22]. Even though these studies are vast, they tend to concentrate on particular elements of technology and its application. However, while there are studies addressing various elements of AM technology, current research lacks the systematization required to offer a comprehensive overview of all the DfMA. It is found that AM construction can be well adopted using current prefabrication techniques.

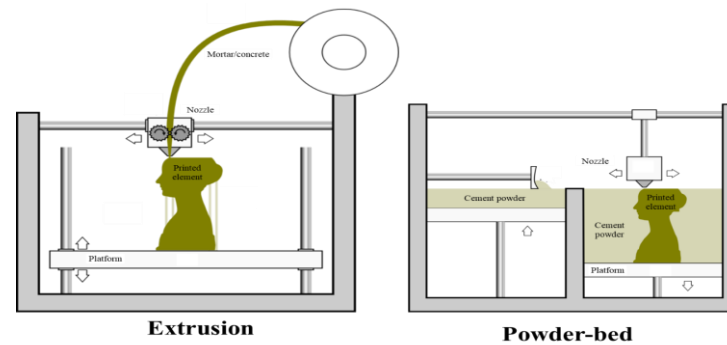**Figure 1.** Recent instances of architectural AM projects.

Figure 2. Concepts of extrusion and powder-bed 3D printing processes.

Prefabrication, sometimes known as offsite manufacturing, has been the subject of a large number of studies that have investigated many different aspects of the practice, including its business models [23-25], advantages and opportunities [26-28], and obstacles and restraints   [29, 30]. The DfMA technique is a set of methods for analyzing and enhancing product design for both economical production and assembly. Very few studies sought to throw light on best practices of design engineers, the manufacturing equivalents of architectural designers, in the design stage, such as the DfMA approach the building [31]. This design procedure ultimately determines the overall building expenditure [32]. Undoubtably, the question that DfMA will direct early on in the process of product design efforts toward cost reduction. This will make it feasible to reach the full lean production potential of the product, since any potential manufacturing challenges and assembly concerns will already have been addressed in the design. This will make it possible to realize the entire lean production potential of the product. This reviewed study identifies 153 pertinent publications in the AEC sector that are related to DfMA, Dfab, and DfAM practices. This review study primarily delivers effectiveness in AM through design, such that innovative approaches can be implemented throughout the design process and give efficiency gains and sustainable building and construction. This is an important step toward achieving AM's full potential.

2. Concept of DfMA

DfMA indicates an overall transition from a sequential, conventional approach to a non-linear, iterative design technique. Numerous DfMA processes and guidelines have been developed to assist designers in implementing this design philosophy to improve designs, productivity, and profitability since its inception during World War II and growth extensively during the 1960s–1970s [33-38].

DfMA consists of two elements: (1) design for assembly (DfA) and (2) design for manufacture (DfM) [39]. DfM focuses mostly on the production of individual components, whereas DfA on their assembly [40]. During 1980s, Boothroyd [41] and Swift et al. [42] developed the main principles of DfA, undertook a series of studies addressing assembly restrictions throughout the design phases. This aids in avoiding manufacturing and assembly problems in later phases of product development [43]. Based on the idea that the lowest assembly cost may be attained by creating a product that can be constructed economically using the best suitable assembly system. Stoll [44] mentioned that the important concept is to create a design with fewer pieces and parts that are still simple to assemble. The fewer components there are, the greater the likelihood that they will all be correctly assembled. To accomplish this, Boothroyd [41] manually offered a variety of ratings for each component in the assembly process depending on the component's ease of handling and insertion. The well-established DfA principles are given in Table 1 (adapted from [45]).

The usage of DfA for 3D printing with an emphasis on component decomposition and assembly-based re-design for AM and the decrease of assembly reorientation and the number of parts through the development of an automatic DfA approach [46]. Robinson et al. [47] parameterized a DfA/DfM-based model. Using DfA and other design

methodologies, El-Nounu et al. [39] redesigned a mechanical assembly using DfA. Also, Manlig and Urban [48] analyzed the link between product development, material flow, and design life cycles for a specific product. In addition, a preliminary cost estimate of a hand pressure mop product was performed using both DfA and DfM [49] . Anyfantis et al. [50] designed multi-material mechanical components using both computer-aided DfA and DfM. Similarly, a strategy for cost-effective design   developed by Favi et al. [51].

Table 1. DfA principles.

	Stage	Explanation
1	Functional analysis	Any material not qualifying for characteristics like relative movement need and adjustment is excluded from the system.
2	Manufacturing process	Selection of materials, quantities, complexity, process, and cost for improved manufacturing.
3	Handling/feeding	A part's ease of manual or automatic assembly is evaluated (termed as feeding).
4	Assembly/jointing	Identifies and scores insertion, fastening, and gripping portions. This examination examines the ease of inserting and connecting pieces. Avoid fasteners.
5	Product group	A product's similar parts, assembly procedure, and routine feedings differentiate it from others.
6	Product structure	Structured information on manufacturing process description, materials selection, process variation for production, economics, design elements, size configurations, and process capabilities for tolerance and surface polish.
7	Component design	The designer is given information on insertion and fastening assembly processes, process capability data, component models, and assembly cost.
8	DfA heuristics	These are usually offered in pairs of "good practice" and "poor practice" examples. Graphically presented heuristic examples are simple to understand.
9	Evaluation assemblies	Two approaches to lower the overall number of components are presented, followed by a full investigation of fitting, handling/feeding, and fixing. Each component/part and assembly procedure is scored to demonstrate complexity.

DfM, on the other hand, evaluates the use of specified materials and manufacturing techniques for the components of an assembly, determines the cost impact of these materials and processes, and identifies the most effective use of the component design [52]. DfM attempts to create parts that are simpler, less expensive, and more efficient to produce [43]. O'Driscoll [53] mentioned that DfM as the process of designing goods with manufacturing in mind, with the objective of reducing manufacturing costs. Furthermore, the author asserted that the premise of DfM is at least 200 years old which was in the field of handcrafted musket industry. RIBA [54] advocated that DfM in construction was the process of planning such that specialized subcontractors could produce important design elements in a manufacturing framework. Panelized systems, such as claddings, have been created this way for years, and now the growing hybrid systems (i.e. unit pods), modular structures (i.e. completely factory-built homes), and 3D concrete printing also apply to the DfM principles.

From the aforementioned explanations of DfM and DfA, it was determined that these two disciplines should be viewed collectively as DfMA [55]. This is due to the fact that modern goods are complicated and the capacity to assemble them efficiently is equally essential. DfMA is a management and software solution that enables designers to address a product's material selection, design, and manufacturability at the outset [56]. Boothroyd [33] advocated the initial DfMA analysis technique, which established methodical processes for analyzing and enhancing product design for both cost-effective production and assembly. Ashley [52] stated that DfMA was strongly presented to other high-tech

industries like aviation, it was labeled as a design review approach that determined the ideal part design, materials selection, assembly, and fabrication activities to generate a cost-effective product. The objective is to give manufacturing input in a logical and structured manner at the conception phase of the design process.

3. Fundamental DfMA aspects in construction

Boothroyd (1994) emphasized that DfA should always be the primary concern, resulting in a simplification of product structure. Next comes the economical selection of materials and procedures, followed by preliminary cost estimations. In order to reach a trade-off choice, cost estimates for the original design and the new (or improved) design will be compared in this step. Once the materials and methods have been finalized, a more complete DfM study may be conducted for the components' detailed design. At this step, DfM is provided with standards for standardization, component design, and component assembly in an effort to lower the total cost of production. The general series of DfMA procedures are illustrated in Figure 3 [33].
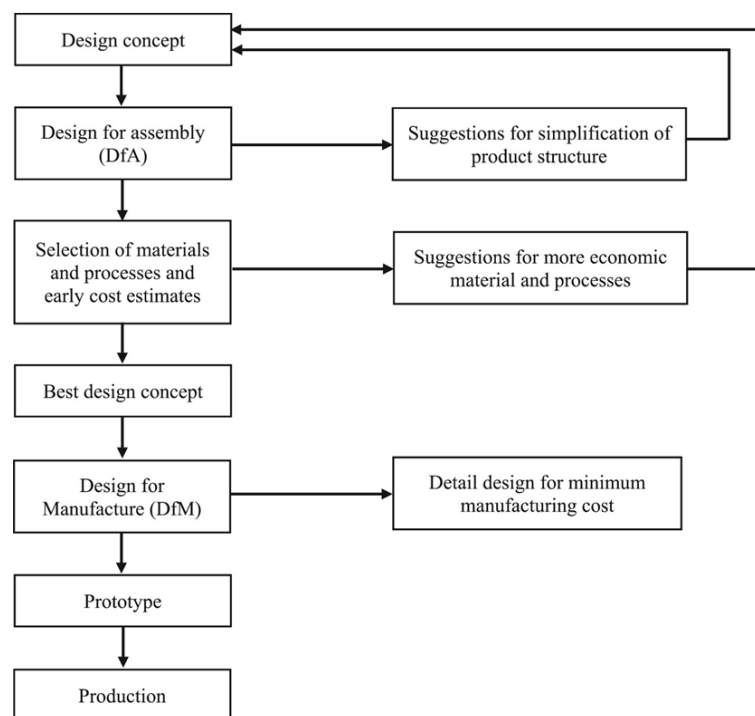

Figure 3. The general series of DfMA procedures [33].

Boothroyd et al. [57]   enlisted the three major concepts or criteria for the application of DfMA to resultant products as shown below:
- The design team reduces the product's structure to save manufacturing and assembly expenses. Moreover, the product structure enhancements are quantified.
- A tool for evaluating items that quantitatively quantifies issues in their manufacture and assembly was developed.
- A tool for reducing costs and negotiating contracts with suppliers was also created.

Bogue [58] stated that there were three means to implement a DfMA procedure. One step is to adhere to a general set of qualitative and non-specific principles or standards and need someone (usually designers and engineers) to interpret and apply them in each unique circumstance. The objective is to include a variety of goods, techniques, and materials. Similarly, Stoll [59] outlined ten DfMA principles and rules: (1) minimizing total number of parts; (2) developing a modular design; (3) utilizing standard components; (4) designing parts to be multifunctional; (5) designing parts for multiple uses; (6) designing parts for ease of fabrication; (7) avoiding separate fasteners; (8) minimizing assembly directions; (9) maximizing compliance; and (10) minimizing handling. Kim et al. [60] also

standardized 13 bridge constructions in the United Kingdom based on DfMA criteria. Jung and Yu [61] recently developed a DfMA checklist to evaluate the optima of design plans for offsite construction projects by outlining optimal design goals, the process, and DfMA principles. The documentation of DfMA process is still in the early stage.

Researchers and building owners are developing interest in modular and prefabricated construction projects based on the DfMA. At these projects, building components are built in a factory and then sent to the construction sites, where they are assembled. Consequently, more research articles concentrating on the essential techniques and technologies for implementing DfMA-based design in sustainable building, renovation, interior projects are being published [20, 62-64]. For example, Serra [65] developed Australia's high-rise construction bathrooms with DfMA-based flat-pack walls saved almost one-third owing to its efficient design. Also, Wasim et al. [66] utilized DfA to quantify the efficiency of prefabricated non-structural timber construction components for residentials. Their case study revealed that DfA of the timber frame and drainage manufacturing system will be 9.8% and 10.244%, respectively. The DfMA can be done for MEP system for improving producibility and product quality throughout the product development process [37].

Exploration of industrial innovation, particularly offsite building, has presented DfMA with a distinct opportunity. DfMA is at the forefront of the industry's cross-sectoral learning and innovation agenda due to the parallels between offsite construction/prefabrication and manufacturing. In addition, rising technical innovations such as Building Information Modelling (BIM) [67-69], 3D printing [4, 70, 71], the Internet of Things (IoTs) [72, 73], and DfMA in particular, new entry opportunities for manufacturing expertise and efficiency improvement.

4. DfMA for Digital fabrication (Dfab) and AM (DfAM)

In this section, two DfMA processes related to Dfab and AM (DfAM) were discussed. The amount of technical publications that represent DfMA for Dfab and DfAM in construction is determined to be quite minimal. Table 2 summarizes the existing 35 publications regarding DfMA for Dfab and DfAM. Relevant research publications currently much emphasized on DfMA for DfAM (76%) in construction as illustrated in Figure 4. The research publication analysis also found that current publications were published after 2018–2023 as shown in Figure 5. Meaningly, the studies on the DfMA for DfAM topic were fairly novel and has been tremendously growing within the five recent years (about 80%).
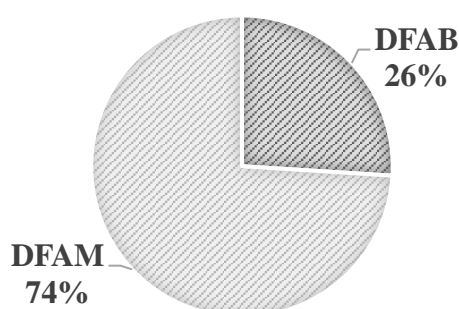

Figure 2. Relative research number of DfMA for DfAM and Dfab in construction (among a total of 35 existing papers).
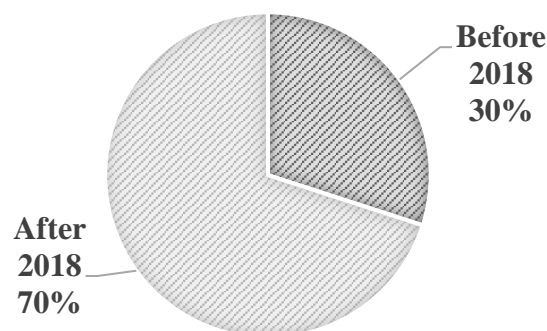
Figure 3. Relative research number of DfMA in construction published before 2018 and after 2018 (among a total of 35 existing papers).

Table 2. The summary of 35 existing publications on DfMA for Dfab and DfAM in construction

Year	Author	Process	Discussion	Reference
2011	Williams et al.	DfAM	Design system focuses on three aspects: identifying essential use-cases, defining formwork systems, and defining software element communication to facilitate expert user cooperation.	[74]
2014	Wang et al.	DfAM	Integration of 3D printing, BIM, and augmented reality is needed to improve architectural visualization in building life cycle.	[75]
2015	Bock & Linner	Dfab	Product structures and information aspects required manufacturing technology for full capability	[35]
2015	Yang&Zhao	DfAM	General Design Theory and Methodology (DTM) can not take use of the enhanced design freedom and process options. Modifying standard DTM and DfAM can help designers effectively use AM in designs.	[76]
2016	Wu et al.	DfAM	BIM and 3Dprinting synergize to provide new DfMA possibilities in the building business. BIM can create an accurate 3D integrated information model for building design and 3D printing.	[5]
2016	Tang&Zhao	DfAM	Few product-level design approaches exist for both functionality and assembly, and some current design methods are challenging to execute due to an unfitted CAD software.	[77]
2016	Tang et al.	DfAM	Establishes the basis for sustainable AM design through functionality integration and component consolidation. DfMA offers designs with fewer parts and less material without sacrificing functionality.	[78]
2016	Kim et al.	Dfab	An interview determines the acceptability of precast bridge components based on DfMA requirements. A case study on a newly completed highway bridge identifies the possibility of precast components selected from suitability analysis.	[60]
2017	Krimi et al.	DfAM	3D printing provides design flexibility and cost savings to build complicated forms, not the time saving.	[79]
2018	Arashpour et al.	DfAM	In advanced façade manufacturing, a substantial portion of the expenditure is for equipment like CNC machines and 3D printers which can be significantly reduced by DfMA.	[80]
2018	Durakovic	DfAM	Most 3D printing studies are still in early stage. This method lacks numerous technologies, therefore maturity will take time.	[81]
2019	Ng&Hall	Dfab	LEAN, DfMA, and Dfab share design to target value and concurrent engineering.	[82]
2019	Dorfler et al.	Dfab	Mesh Mould is a novel construction technology for non-standard reinforced concrete buildings employing a mobile robot on site.	[83]

2019	Hinchy	DfAM	3D printing is ideal for low-volume, sophisticated components, hence it should be selected over traditional methods. Build orientation and support structures effect manufacturing cost, time, post-processing, and final component mechanical characteristics.	[84]
2019	Medelling-Castillo&Zaragoza-Siqueiros	DfAM	Build orientation affects component stability during construction by determining the part's support surface on the building platform.	[85]
2020	Ng et al.	Dfab	Dfab manager and Dfab BIM coordinators are needed early in the design process.	[86]
2020	Alfaify et al.	DfAM	The suggested DfAM solutions include cellular structures, component consolidation and assembly, materials, support structures, build orientation, part complexity, and product sustainability.	[87]
2020	Vaneker et al.	DfAM	DfMA attempts to optimize product design to deal with complicated production processes while specifying 3D printed product advantages throughout its consumption phases.	[88]
2020	Ghaffar et al.	DfAM	Collaboration across materials science, architecture/design, computer, and robotics is important to developing and implementing 3D printing.	[89]
2021	Gibson et al.	DfAM	Modern 3D printing has led to more emphasis on DfAM training.	[90]
2020	Frascio et al.	DfAM	This solution tackles the exponential link between construction volume and printer cost and improves efficiency by deploying many 3D printers simultaneously.	[91]
2021	Ng et al.	Dfab	Three design practices were identified: post-rationalization, mass customization, and modularization.	[92]
2021	Graser et al.	Dfab	Three theoretical factors for using Dfab house projects: full-scale projects are an effective Dfab strategy in AEC; large-scale implementation promotes Dfab's acceptability in AEC; and projects help develop a new Dfab paradigm.	[93]
2021	Ghiasian	DfAM	Intelligent machine learning-based recommender system that identifies part candidates and addresses AM infeasibilities unexisting component designs.	[94]
2021	Prasittisopin et al.	DfAM	Small modules for 3D-printed pavilions cab be attached together using bolt-nut designs	[18]
2021	Morin and Kim	DfAM	The optimization scheme's effectiveness in breaking a cantilever beam structure into components that fulfill the AM build plate's geometric restrictions while reducing the structural impact of joints.	[95]
2021	Vu et al.	DfAM	DfMA framework entails three main elements: Structure, Property and Process.	[96]
2022	Ng et al.	Dfab	Proposed seven strategy propositions to achieve the benefits of adopting Dfab system.	[71]
2022	Rankohi et al.	DfAM	Integration of 3D printing, DfMA, and BIM can boost automation and productivity even with present labor difficulties.	[97]
2022	Sadakorn et al.	DfAM	Similar to the precast method, the jointing can be executed in dry process.	[98]
2022	Nguyen et al.	DfAM	Parametric model for bridge pier improved industrial output.	[4]
2022	Spuller	DfAM	Unlike product design application, construction occasionally uses DfAM.	[99]
2022	Song et al.	DfAM	New DfAM knowledge must be organized into general frameworks to assist practitioners throughout the product design process and to properly leverage present AM capabilities and developing potentials.	[100]
2022	Qin et al.	DfAM	Machine learning has contributed significantly to DfAM and has the potential to revolutionize AM.	[101]

| 2023 | Rehman et al. | Dfab | Two most important liability factors are management capability and BI.M | [73] |

4.1. DfMA for Dfab

Dfab is rising as a systematic breakthrough in the AEC sector to stimulate automation and enhance efficiency. It is necessary to incorporate knowledge about the manufacturing process at an early point in the design process. A paperless design and construction process can be supported by Dfab, which results in cost savings [102]. In addition, it offers a number of environmental, social, and economic advantages, including the reduction of waste, the removal of physical inventory, the reduction of labor, the implementation of digital quality control, and the establishment of off-line part setup [103]. The typical Dfab techniques consist of two methods computer numerical control (CNC) and laser cutting. Based on DfMA, Bridgewater [104] suggests Design for Automation (DfA) for factory-based production and on-site automation to reduce the number of components for Dfab like robotics. He also mentioned rules for redesigning building systems for DfA, as well as a new type of construction contract and legal requirements for DfA. Bonwetsch [105] advocated that CNC let design information be sent directly and automatically to fabrication machines. Robotics puts an emphasis on integrating design and construction, which helps to cut down on construction costs and time and improve the quality of design. Examples how DfMA works for robotics and how codes and designs could be combined early in the design process were addressed.

The parameters found by Dfab could affect the design results and the design process. During the design process, all physical constraints of fabrication had to be taken into account. Martinez et al. [106] indicated how the robotized Field Factory System was designed using DfMA principles and how its production lines were set up. For instance, the factory layout took into account the size and range of motion of an ABB robot. The Service Core has been examined to improve the time and quality of assembly holistically. Montali et al. [107] determined the Knowledge-Based Engineering (KBE) approach using digital tools to support design through automation of reusable knowledge on facade design with DfMA principles. They found that the 2D and 3D digital tools that are currently available could not close the design-manufacturability gap in the facade construction industry. The DfMA-based KBE for design automation is proposed to guide design from the beginning of the design process to improve quality, reduce delivery time and costs, cut down on rework, and support product development in construction. Also, CNC milling was conducted to investigate the principles of DfMA [80]. Ng and Hall [92] conducted online game with Target Value Design (TVD) principle for modelled the Dfab construction. TBD principle implies a strategy that is built on lean principles and incorporates design based on thorough cost estimates [108, 109]. Concurrent engineering, design-to-target-values, and the maximization of values to project stakeholders are possibly done by TVD. They found that TVD has been offered as a feasible design management strategy for managing Dfab during the design process and maximizing value for project stakeholders. However, the application of Dfab in TVD in the construction sector is still relatively new. The prerequisite for future assessment is required. Parametric modeling also supports collaborative work, which makes it easier to put DfMA into practice. Ng [110] reviewed 59 journal articles about Dfab and talked about how DfMA has several important enablers. These include Dfab engineers, parametric or computational resources, visual-programming conditions, bespoke/customized design and modular features, digital fabrication optimizing and prefabrication processes, artifact of digital fabrication physical mockup, value of reducing human dependence, along with risks of increasing uncertainty in production and performance compromise/uncertainty. De Soto et al. [111] determined the productivity, cost, and time aspects on the on-site robotic fabrication technology. Results found that complex decoration structures can be made with Dfab at no extra cost. This is because Dfab can build a part in a more integrated way by getting feedback early in the design process, as also discussed in the full-scale Dfab house under NEST project developed by

EMPA, Switzerland [112]. Regardless of the fact that only a limited number of investigations have been performed on Dfab technology at the present, these Dfab principles are apparently in accordance with the DfMA principles and may be adopted without issue.

4.2   DfMA for DfAM

DfMA tools facilitate communication between product designers, production engineers, and any other stakeholders to the finished product. Barbosa [113] asserted that DfMA has been an essential method for boosting productivity of any product development via design in several manufacturing sectors. However, the AEC sector has not given building designers with similar techniques. In an increasingly dispersed work environment, the integration of construction expertise into the design phases continues to rely on the experience of individuals [114]. Furthermore, Spuller [99] mentioned that in contrast to the domain of product design, the building sector makes relatively infrequent use of these DfAM methodologies.

In Figure 6, the complexity levels of DfAM techniques are exhibited. Both direct component replacement and DfAM can be viewed as process of manufacturing-driven and function-driven design strategies, respectively. The adaption of AM represents the medium ground between the two sides. To take advantage of AM, the design of a component can be modified, but its connections to other components are maintained in their previous states [115].
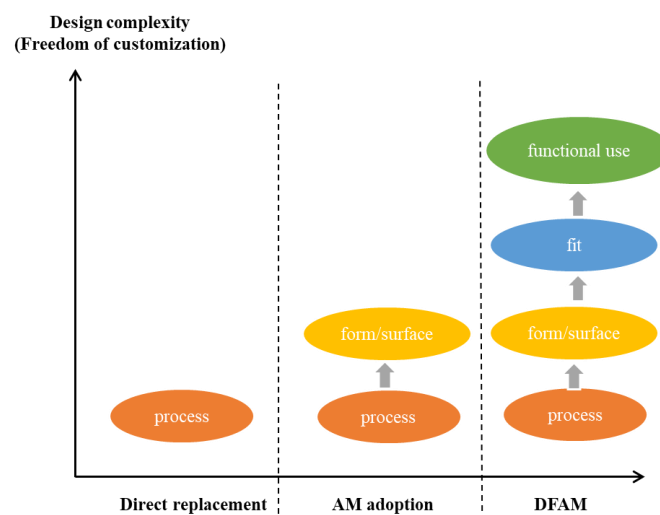

Figure 4. Complexity levels of DfAM.

First, the direct replacement (leftward) is the basic design process for manufacturing process.   From a traditional manufacturing standpoint, the Handbook for Product Design Design for Manufacture by Bralia [116] and Product Design for Manufacture and Assembly by Boothroyd et al. [57] addressed suitable instances of design for manufacturing standards and practices. The substantial work on design for manufacturing over many years indicate the complexity and pervasiveness of the design for manufacturing concerns [117]. It is necessary for designers to have a solid grasp of the limits imposed by accessible fabrication technologies. Some of these restrictions are alleviated by AM, while others are not. The applicability challenges for design for manufacturing in AM are shown in the following areas where traditional design for manufacturing falls short of the benefits offered by AM. The applicability challenges include:

- Layerwise operational characteristics and direct CAD model production extend part design creativity.
- Parts could be created as modular 3D puzzles incorporating small modules.
- As AM materials may be treated point-by-point or layer-by-layer, complicated material compositions and property gradients are possibly adopted.

- AM allows for the fabrication of hierarchically complicated, long-scale building designs.

AM's distinctive technique allows for low-cost, fast remanufacturing and repair.

AM capabilities represent the complexity of shapes and surfaces in designs. It is feasible to create almost any form, allowing for lot sizes as small as one, rapid customization of geometries, and shape optimization. Some studies determined using inner truss as a surface of the architectural wall structure of the building [98, 118]. Results indicated that several patterned AM wall structure could be created based on geometric ratio. This led to the reduction of material consumption and printing time. Nguyen et al. [119] developed bridge constructions that are prefabricated using AM adoption. Throughout this work, a unique digital engineering model approach was developed by combining current knowledge of DfMA with structure-oriented parametric modeling technology. The geometrically complex elements of bridge piers that were aligned with the aesthetic surfaces were built using DfMA approaches and parametric modeling. The developed AM bridge pier was shown in Figure 7.
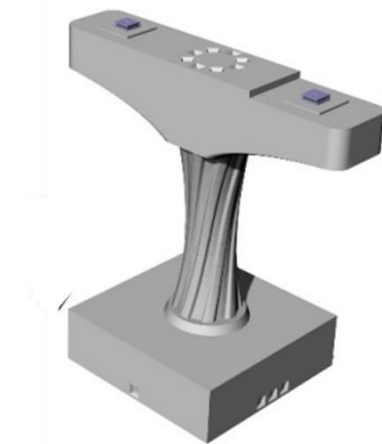
Figure 7. Digital modeling of prefabricated AM bridge pier [119].

Lastly, the DfAM as shown in the rightward of Figure 5 entails two additional steps (fit and functional use). The "fit" term means the assembly process. To reduce assembly time, cost, and challenges in conventional assembly, two primary ideas are frequently offered: reduce the number of pieces and eliminate fasteners. Both factors immediately result into fewer assembly procedures, which is the main cost driver for assembly [57]. Mavroidis [120] stated that, conventionally, the primary role of assembly is to link together components, freeform material, and small elements   to create a complex product. In contrast to typical assembly processes, AM permits the consolidation of elements in locations where they were previously manufactured independently owing to manufacturing restrictions, material difference, or cost. AM reduces manufacturing limits and gives a fundamentally different viewpoint on jointing than conventional assembly. The issues associated with design considerations for AM assembly are covered as follow:

- The layer-by-layer or point-by-point nature of AM makes it easier to combine parts and embed them. Most applications can be put into two groups: those that use operational mechanisms and those that use embedded components. In the case of operational mechanisms, if two or more parts need to be able to move in relation to each other, AM can build these parts already put together. For this type of non-assembly mechanism, one of the most important factors is joint clearance [121]. The joint clearance can reform the way the mechanism works. Besides, in the case of embedded components, it is often essential in building a functional prototype by putting components into a part. This can improve the performance of the holistically system.
- AM is a good way to joint more than one material together. The use of more than one material in AM to improve part functionality. The multiple nozzle heads of extrusion AM has been examined [19, 122, 123]. Classen et al. [95] made fork-shaped, multi-

nozzle extrusion heads for layer thicknesses of 50–100 mm and filament widths of 180–240 mm, as illustrated in Figure 8. The goal was to set up a fully automated, high-speed process for making continuously steel-reinforced concrete walls. Khoshnevis et al. [124] introduced supporting material, such as wax and sand, along with the concrete nozzle. This can be adopted for better buildability and can be built the roof structure. Aside from these, multi-nozzle AM can produce complicated structures such as concrete extruded nozzles and spraying nozzles for smoothing the surface of the structure and creating a range of surface textures.
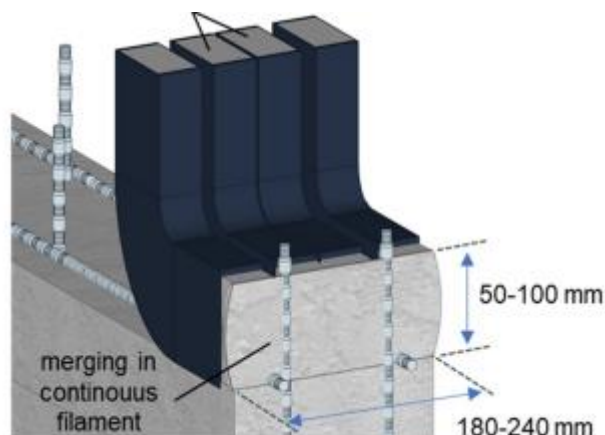

Figure 8. Multiple-nozzle print head for steel-reinforced concrete walls and two layers of steel reinforcement [95].

Another step shown in Figure 6 is the "functional use" which can be mainly structural performance as a structural building component. Historically, products with basic geometries have been favored despite losing functionality or performance. To increase structural performance, AM structures are designed to be multifunctional and adaptable. The capability of DfAM to generate extremely flexible and functionally integrated components encourages the development of intelligent components that rapidly adapt to and respond to the operating environment. Another virtue of AM is that it can be printed freeform, allowing for the creation of cellular structures. On the basis of the topology optimization principle, it is possible to design a hollow structure that results in less weight and decreased material consumption. Nauyen and Vignat [125] asserted that the topology optimization approach permitted the identification of an optimal material distribution and the reduction of material consumption while maintaining the mechanical qualities of the product. Additionally, in the case study of AM bridge piers, by relating the DfAM parameters to the estimated moment–curvature curves, the seismic performance of a bridge pier analyzed by finite element method was achievable [119]. Vu et al. [96] advocated that optimized micro-structures could be self-supporting only in particular instances, such as when the load is equally distributed and the micro-structures were anisotropic. Moreover, Morin and Kim [126] assessed the topology optimization of AM element for DfAM when build area is limited. From their work, a structural cantilever beam case study is employed. Preliminary findings show the optimization scheme's usefulness in decomposing the cantilever beam structure into components that fulfill the AM build plate's geometric restrictions.

In addition to structural performance aspect, other functional purposes such as thermal and acoustic insulation performance, MEP, and HVAC systems can be designed into the AM structure. Prasittisopin et al. [22] developed textured AM wall with hollow structure allowed the structure   to perform thermal resistance to sunlight in tropical climate. The AM wall could end up for electricity expenditure by almost 50%. Karadeniz and Toksoy [127] also mentioned that the HVAC system can be successfully implemented in AM through DfAM, followed by HRVU and AHU units. DfAM methods are designed to aid designers in making decisions at the design stage to fulfill functional requirements while

maintaining manufacturability in AM systems, and to aid manufacturers in the fabrication of components using AM systems [85]. DfAM includes four steps for process, form/surface, assembly, and functional use, allowing for greater levels of design complexity or customization freedom.

Overall research papers were reviewed, and topics emphasized relate to DfMA for Dfab and DfMA for DfAM were categorized. The relevant topics determined entail product structure/performance, reference case, management (i.e. collaboration, training, and lean engineering), BIM, machine learning, CAD, modifying standard, and visualization. Figure 9 exhibits the relative research number of DfMA for DfAM and Dfab relating to eight different themes. Existing knowledge is still performed in the areas of product structure/performance, management on collaboration, training, and lean engineering, and adequate reference practices. Following the DfMA based on BIM, which can result in the digitization of building models throughout the manufacturing and assembly operations. Few DfMA studies for construction have been conducted involved in machine learning, CAD, standard modification, and digital visualization technique like virtual reality.
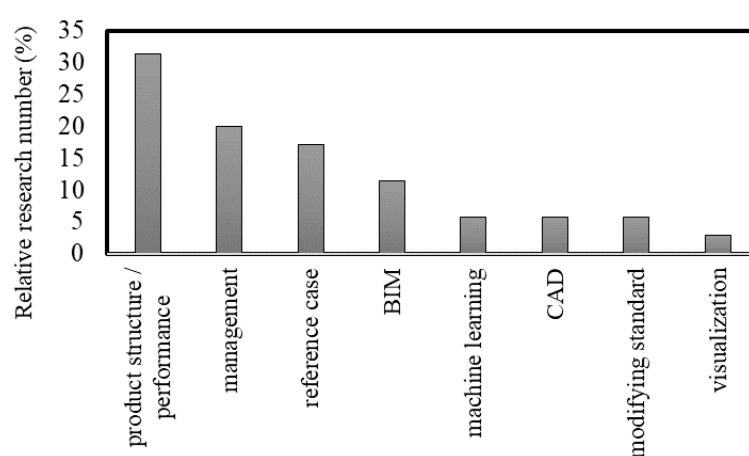

Figure 5. Relative research number of DfMA for DfAM and Dfab relating to various topics.

5.   Jointing design for AM structure

Some investigation programs determined the jointing process for prefabrication and cantilevered beam structure [18, 95]. In the case study of DfAM for the cantilevered beam, the edges of the partitioning rectangles reflect the partitioning lines that divide the structure into components that can fit within the AM machine. To represent the structural impact of building a multicomponent system, joints are modeled at the dividing rectangle's borders. For optimization purposes, it is assumed that the joint material qualities are 15% weaker than the structural material properties. The decomposed design can be impacted by the jointing design.

For AM concrete pavilion, small modules were printed and then fabricated. Each module's joint assembly procedure consisted of two steps: (1) finding the connection location and (2) jointing the small modules. The location for installing an anchor bolt at a joint is defined. Figure 10 depicts the locations of the joint regions and joint assembly processes. First, the flat surfaces of each module were closely joined, and each module's height was split into five portions. Each part's height was dependent on the module's height, and two-thirds of each section was positioned in the joint area. It was proposed that the junction location be positioned roughly 150 millimeters within the outer shell to guarantee a secure connection between the two portions. It was proposed that the junction was secured using a 6.8-centimeter-long (2.7-inch-long) anchor bolt. The angle of the anchor bolts was parallel to the shell's flat surface. Then, the joint system was built to connect each module with high precision and accuracy. Anchor bolts and studs were used to install each module. To build the assembly as planned, the piercing operation must be performed with precision. After the studs were inserted, knots were used to connect each module. All anchor bolts,

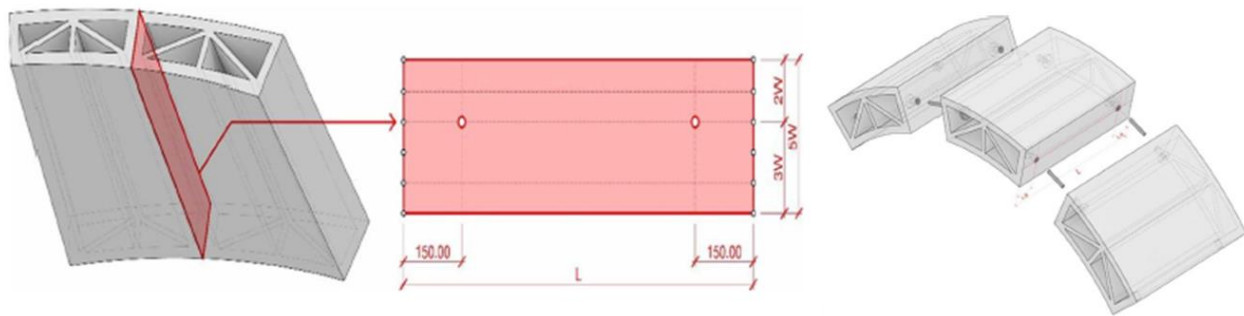studs, and knots were proposed to be adapted from a stainless material, such as zinc-coated galvanized steel.

Figure 10. Location of the joint region and joint assembly processes of 3D printing pavilion.

Another joint design of AM load-bearing wall structure incorporating concrete material according to Sadakorn et al. [98] has been mentioned. They proposed employing steel plate in dry production similarly to precast wall parts. Figure 11 shows the precast wall element's steel plate and two bolts joint connection. Middle wall panels are where the bolts enter. The planned DfMA solution of AM wall panels is readily accessible. The suggested wall panel junction dimensions were also displayed. The AM load-bearing walls are jointed at both ends with projecting fins. The lift-up component must have an open hole that may be filled with cement and inserted in the lifting point. Horizontal wall joins are steel plates, 6.5 x 12.5 cm and 4 mm thick, with holes for tightening nuts to save installation time on site. The joint area is concave inward. The joints can be covered with cement plaster after installation to protect from leakages.

Frascio et al. [91] reviewed the jointing methods with adherends and adhesives. They discussed a variety of tailoring techniques for additively made adherends and adhesives, with the goal of optimizing the performance of bonded joints. Customizing AM adherends and adhesives according to DfMA strategy has shown to be a very effective, although mostly unexploited method for enhancing the performance of adhesively bonded joints.
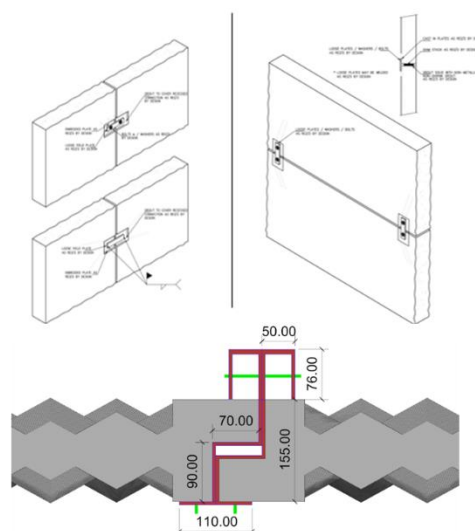

Figure 11. Dry joint design of AM load-bearing wall structure.

6   Machine learning for DfAM

Machine learning is defined as "allowing computers to solve problems without being specifically programmed to do so" [128]. Due to the availability of vast amounts of data, the advancement of computer technology, and the improvement in the efficacy of

accessible machine learning techniques, it is becoming very interesting topics nowadays. Several machine learning techniques in DfAM have been successfully developed in wide ranges of applications. The main applications highly adopt machine learning are such as aerospace, automobile, and defense. These include multi-stage Bayesian surrogate models [129-131], artificial neuron network (ANN) [132-135], inductive design exploration method [136-138], support vector machine [69, 139, 140], graph convolutional networks [141, 142], surfel convolutional neural network [143], multi-task Gaussian process learning algorithm [144], computational fluid dynamics model [145, 146],   back propagation neural network [147], and particle swarm optimization method [148, 149].

In terms of geometric flexibility and highly interconnected structures, AM has enabled novel designs and performance improvements in product development [150]. The benefits of using machine learning can be implemented in several DfAM aspects. The machine learning can be beneficial in following areas: (1) conceptual design phase, (2) design optimization, (3) geometry deviation prediction from build orientations and thermal deviations, (4) material analytics (such as material properties, material chemistry, material multi-structure, and resultant performance), (5) prediction of defect in quality assurance process by image analysis, sensor signal methods, and (6) prediction of final product performance, total costs, energy consumption, and carbon emissions. Due to the unique production paradigm of AM, batch sizes, production schedules, and cost drivers may differ from those of conventional techniques. It also necessitates distinct methods of metrology and quality control. Therefore, DfAM has been presented as a means to provide AM design experts with a comprehensive set of design and analysis tools for complicated component structures and AM processes. Typically, DfAM consists of two primary study topics: component design and design optimization [151]. AM offers free shapes and bespoke geometries for component design, enabling the production of intricate internal elements to boost functionality and improve performance of target parts, providing designers with a vast amount of creative flexibility. AM component designers must define production route methods, part placements, build orientations, and support structures to improve the quality of final printed items in order to optimize the design. The machine learning technologies have been increasingly utilized to DfAM in recent years [137] because to advancements in artificial intelligence, IoT, and data availability [101].

Very little machine learning research on the issue of DfAM for construction have been undertaken. Qin et al. [101] reviewed 222 latest research publications regarding machine learning for AM in several industries. However, only one paper was published based on using machine learning for DfAM with concrete material conducted by Lao et al. [152]. The researchers used an ANN model to establish a correlation between the nozzle and extrudate geometries. Upon completion of model development, a nozzle-extrudate database was created so that the ideal nozzle shape for a given goal extrude shape could be analyzed. Table 2 illustrates a summary of the process flow. During the pre-testing phase, the training data for the ANN model was compiled. After topology optimization, the predictive ANN model is then trained. By linking randomly produced nozzle geometries to their anticipated extrudate cross-sectional shapes, a database was created using the ANN model. Finally, nozzles for various target extrudate cross-sectional shapes may be retrieved from the database and employed in the printing process. The findings demonstrate that the suggested method enhances the surface quality of different structures with distinct contours.

Table 1. Summary of the workflow to identifle nozzle shape using ANN model.

Workflow	Discussion
Pre-testing	Set up nozzle experiments and perform experiments
ANN model	Optimize topology, train, and validate
Establish database	Generate sufficient volume randomly and predict extrudate shape
Target extrudate cross-sectional shapes	Analyze target shape, find nozzle shape, and perform printing

Further recent publication of machine learning of DfAM in the object construction field conducted by Ko et al. [153] was present, even though it is not for the building. They employed a machine learning algorithm of Classification and Regression Tree on measurement data from National Institute of Standards and Technology for construction of a Laser Powder Bed design rule. Several construction members can be obtained using machine learning algorithm include overhang, hole, beam, wall, cylinder, sphere, thin wall, and support structure. The material property also be parameterized such as material distribution, material type, and thermal property. Many research programs can be extensively carried out on the machine learning of DfAM for AEC industry.

7   Conclusion and suggested future works

The state-of-art review of the DfMA for Dfab and DfAM were performed to discuss the adoption in AEC industry on various aspects, entailing DfMA concept, DfMA implementation in construction, DfMA for Dfab and DfAM, Jointing design for AM assembly, and machine learning for DfAM. The key annotations from publication 1980s to recent developments were discussed as follows:

1. AM using concrete materials also applies to the DfM and DfA principles suitably.

2. Increasingly advanced technical developments in construction, such as AM and DfMA in particular, new entrance prospects for manufacturing technology, and improvements in production efficiency.

3. Most research (80%) has been investigated within these 5-year period.

4. The majority of research, which accounts for 80 percent, has been investigated within these five years.

5. DfAM allows for a greater degree of design complexity as well as a larger range of freedom in terms of customization. It consists of four stages: process, form/surface, assembly, and functional usage.

6. Existing knowledge is still applied to the product structure/performance, management, and BIM integration domains.

7. Anchor bolt and stud fabrication is viable options for achieving joint design in an AM wall structure. Additionally, the dry joint techniques of AM wall structure can be done as like manner to the precast wall system.

8. Although many machine learning methods for DfAM has been studied in a variety of applications, only one or two research programs have been conducted in the building industry.

DfMA has lately been adopted in modern construction technologies such as prefabrication and offsite construction, and several future studies may be conducted in various facets including formal documentation, general case practices, and design process management. Regarding this review, it was apparently revealed that the DfMA in Dfab and DfAM is deficient since the new reference cases are still confined. It is possible to get the current DfMA for integration within design and construction, repair, renovation, and rehabilitation, leaving a large gap for researchers to fill so that the DfMA can provide significant advantages to the AEC sector. This is a crucial step towards realizing AM's full potential.

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