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Applicability analysis of additive manufacturing methods in construction projects

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Subject review

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Additive manufacturing (AM) technologies, also known as 3D-printing systems, have been rapidly gaining popularity in the construction industry. Recent developments in additive manufacturing technologies indicate that large-scale 3D printing systems have significant potential for providing a fully automated construction. The applicability of 3D printing on the construction scale is analysed in the paper in terms of AM methods and materials.

Key words:
3D printing, additive manufacturing technology, additive construction methods, automation, construction projects

Pregledni rad

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Analiza primjenjivosti metoda aditivne proizvodnje u građevinskim projektima

Tehnologije aditivne proizvodnje (AM), poznate i kao sustavi 3D-ispisa, brzo dobivaju na popularnosti u građevinarstvu. Razvoj tehnologija aditivne proizvodnje u novije vrijeme pokazuje da veliki sustavi 3D-ispisa imaju značajan potencijal za potpuno automatizirano građenje. U radu se analizira primjenjivost 3D-ispisa u građevinarstvu iz aspekta primjenjivosti tehnologija aditivne proizvodnje i materijala.

Ključne riječi:
3D ispis, tehnologija aditivne proizvodnje, aditivne metode gradnje, automatizacija, građevinski projekti

Übersichtsarbeit

Fahriye Hilal Halicioglu, Seckin Koralay

Analyse der Anwendbarkeit additiver Fertigungsmethoden bei Bauprojekten

Die additiven Fertigungstechnologien (AM), bekannt auch als 3-D-Druck-Systeme, werden in der Bauindustrie immer beliebter. Die Entwicklung von additiven Fertigungstechnologien zeigt in jüngster Zeit, dass große 3-D-Druck-Systeme ein erhebliches Potenzial für eine vollständige automatisierte Konstruktion haben. In der Abhandlung wird die Anwendbarkeit von 3-D-Drucken in der Bauindustrie unter dem Gesichtspunkt der Anwendbarkeit additiver Fertigungs - und Materialtechnologien analysiert.

Schlüsselwörter:
3D-Druck, additive Fertigungstechnologie, additive Baumethode, Automatisierung, Bauprojekte

1. Introduction

The term "automation" is derived from the ancient Greek word "auto", acting by itself. When referring to "construction automation", it logically means that the construction is emerging by itself without any human intervention. To describe it more extensively, Castro-Lacouture [1] defines it as "the technology-driven method of streamlining construction processes with the intention of improving safety, productivity, constructability, scheduling or control, while providing project stakeholders with a tool for prompt and accurate decision making."

The automation technologies from other large-scale manufacturing industries (automotive, aerospace, shipbuilding etc.) started to move toward construction industry in the early 20th century with the emergence of mass production systems [2]. At first, building elements were being streamlined as prefabricated components and assembled on the construction site. Nevertheless, in this approach the level of automation remained limited to "off-site" fabrication. The assembling process was being handled mainly by human labourers. On-site construction automation first came into existence through the use of robotics back in 1970s Japan with the investments by a group of large construction companies called "Big Five" (Shimizu, Taisei, Kajima, Obayashi and Takenaka). Developments mainly started due to the aging population and, secondly, due to the fact that construction jobs were found unappealing by younger generations who considered them as difficult, dirty and dangerous [3]. For these reasons, two main approaches were put forward. Firstly, "single task construction robots" were developed in order to replace workers on the construction site by executing very specific tasks like painting, trowelling, and ceramic tiling. Secondly, the robotic systems were further improved through "construction automation systems" that aim at full scale automation by coordinating a variety of subsystems supported by single task construction robots. The main focus of these two concepts is the automated on-site assembly of prefabricated building components. Nonetheless, the whole robotic process is still a replication of the usual complicated human work-chain and, also, the dependence on prefabricated components brings its own drawbacks such as the necessity of specialized off-site production networks for standardized (monotone) elements [4]. At this point, additive manufacturing (AM) approach has some complementary aspects and the potential to support construction automation since it may allow robotic production of customized building components directly from the raw materials in an efficient way [5].

The AM technologies initially came into existence in 1980s [6]. Charles Hull [7] developed the first AM machine called stereolithography as a substitute to the injection moulding technique (a formative manufacturing method), which he was using to create metal parts. That formative technique was costly and time consuming as it required forming a new mould for each different part [8]. His new system was relying on automated solidification of a UV-sensitive fluid that forms the 3D object by building each cross-section of the geometry step by step, so he could produce the parts without any need for a mould. In 1984, Hull patented his invention under the name "Apparatus for production of three-dimensional objects by stereolithography" and described the technology as "rapid, reliable, accurate and economical" [7]. Afterwards, with the development of more advanced systems, AM technology became more and more promising and also preferable to other techniques. Campbell et al. [9] state several reasons why this technology should be preferred: ability to fulfil user-fit requirement, improved functionality, parts consolidation, and aesthetics. In addition, it has an extensive range of possible material options to utilize [10] and does not create waste material**s** like in subtractive methods which form the objects by cutting, curving, drilling, etc. [11]. Recent developments in AM technologies show that the large-scale 3D printing systems have great potential to provide for fully automated construction. This paper discusses the applicability of 3D printing on the construction scale in terms of AM methods and materials.

2. Additive manufacturing: definition and process characteristics

Since invention of early systems for layer by layer manufacturing, various labels have been put forward to call them and some of the historical terms used to name the technology are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication, and freeform fabrication. However, "3-dimensional (3D) printing" and "additive manufacturing (AM)" are currently the most accepted ones and they are used as synonym to each other. While the term "3D printing" is commercially popularized and widely used in general public, "additive manufacturing" is rather the technical term accepted by the manufacturing industries and by the standards organizations such as ISO and ASTM [9, 12].

To clarify what exactly the AM technology is, various definitions can be found in the literature. These are mainly based on describing a general process that could include every type of current printing methods. It can be expected that the definitions given will be exposed to some changes in the near future when new approaches are developed.

According to a definition given by Bogue [10], "3D printing technology is an automated, additive manufacturing process for producing 3D solid objects from a digital (i.e. CAD) model." The term "3D printing" refers to the way of consecutively using the solidified material layer upon layer, so that it allows the printing of objects beyond two-dimensional applications [6].

ISO/ASTM 52900:2015 [12], developed as a common set of standards on AM by bringing ISO/TC 261 and ASTM F42 together, describes general principles and terminology of AM. According to this code, AM is "a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and

Figure 1. Schematic comparison of (left) subtractive, (middle) formative and (right) additive manufacturing methods [13]

formative manufacturing methodologies." 3D printing should not be confused with subtractive and formative manufacturing which are also methods for creating a three-dimensional physical object (Figure 1). In subtractive method, the object is created by removing material by drilling, milling, grinding in contrast to additive manufacturing. In formative manufacturing, the object is created by pouring the material in a cast or a mould. Based on the above-mentioned definitions, the main characteristics of the AM process can be stated as follows:

Phase I: Characteristics related to the virtual production stage

- *Characteristic I (Digitally created instructive virtual model data):* The overall information relating to the end-product is initially stored as a virtual representation in the form of a sequence of primary units which create a language of information. For a digital file, these primary units are binary numbers, 0 and 1. The data contains basically the information about the 3D geometry. Additionally, it may also include the information about materials, colours, production process, etc.
- *Characteristic II (Generated by computing devices):* Computers can automate some steps of the process like generating a parametric geometry, creating a texture, setting the instructions. Nevertheless, for now, it is mostly human mind that decides, designs, and controls the model. So, the automation of the whole process is limited and it is unlikely to be fully automated until the time the use of advanced artificially intelligent minds instead of human reasoning becomes possible.

Phase II: Characteristics related to physical production stage

- *Characteristic III (Additively produced physical product):* The physical product is created in an additive manner following a pre-determined pattern to create the 3D object. Either one or more than one type of material can be used, with various possible forms and phases, by adding a certain quantity each time during the process.
- *Characteristic IV (Automated by the robotic vehicles):* The additive production process is conducted by equipment which functions by itself and requires minimum or no human intervention. The printing robots mainly follow the instructions defined in the virtual data.

Though AM technologies differ according to various purposes and needs, the basic features of the process are very similar. Gardan [14] describes a generic AM process named as "AM engineering and manufacturing cycle" including eight main steps as noted below (also shown in Figure 2):

- *Generating geometry of virtual model:* The model is either designed in CAD software or obtained by 3D scanning of a physical model (reverse engineering). Some of the possible file formats are dwg, 3ds, c4d, blend and skp. These files contain the 3D geometry information.
- *Engineering geometry of virtual model:* Analysing, modifying and optimizing the initial virtual model to make it convenient for manufacturing. Virtual geometry should match the laws of physics in the real world and also fulfil the efficiency requirements.
- *Generating intermediate virtual model:* The virtual geometry is converted into a 3D printing file format that can be used broadly in any device and method. Some of the possible file formats are STL (stereolithography file), VRML (virtual reality modelling language) and AMF (additive manufacturing file) [15]. STL is a more common format, but it enables only monochrome products and has limited options. Therefore, AMF format tend to be the international standard as it contains dimensional units, materials, colours, and some other features [16]. AMF is also accepted by ISO/ASTM.
- *Transferring intermediate model data: 3*D printing file is transferred to the integrated software of the AM machine.
- *Preparing AM machine for printing:* The machine is configured, materials and positioning of the equipment are checked. Supports and scaffolds are positioned on to the set to avoid collapse of the geometry during 3D printing process.
- *Generating virtual manufacturing model:* The integrated software of the 3D printing device converts the intermediate file into its own specific file format that is usually patented by the printer company. This new file contains all the information about how the process will be performed, such as "what are the layers and their thicknesses," "at which point will the printer start to produce," and "what printing route will the printer follow."
- *Production:* The virtual model is manufactured physically layer by layer following the pathway given by the model data. This process is usually fully automated.

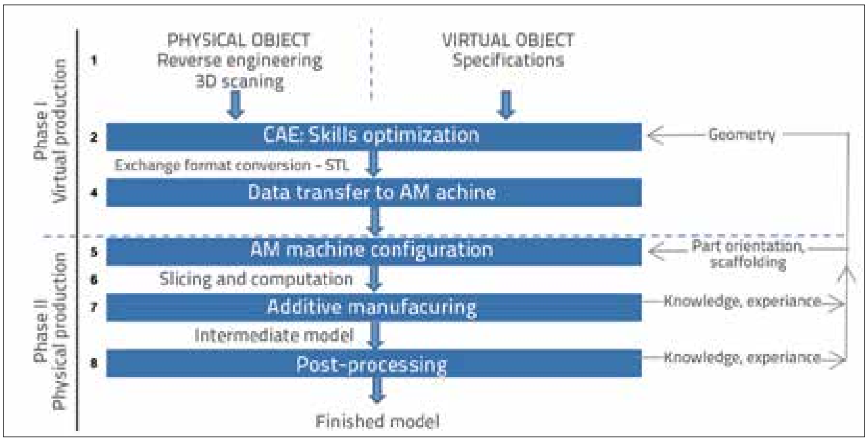

Figure 2. Eight main steps of generic AM process adapted from Gardan's AM engineering and manufacturing cycle [14]

- *Post-production:* If necessary, the product can be further treated. Hardening, infiltration, colouring, and polishing are some of possible treatments.

2.1. Methods used in additive manufacturing (AM)

AM technologies are mainly aimed for automated tailoring and low-volume manufacturing where mass production is insufficient. Former systems were at desktop-scale and mostly used for purposes such as concept modelling, rapid-prototyping, rapid-tooling, and replacement part production. Numerous AM methods have emerged since the appearance of the early printing systems in the 1980's [15]. As it is well known, patents provide valuable information on technological developments. Thus, the present study investigated current patents on AM in order to have a better understanding of the AM methods. Major patents relating to AM technologies are presented below in chronological order:

- In 1984, Charles Hull, who founded 3D Systems company, patented his stereolithography (the term 'stereolithography' is derived from the ancient Greek words stereos (solid), lithos (stone) and graphia (writing), meaning 'writing with solid stone') machine, which uses fluid photo-curable polymer in a vat. This fluid is solidified by an UV-light beam that scans each cross section of the desired article [7].
- In 1986, another AM technique was patented by Carl Deckard with the file name "Apparatus for producing parts by selective sintering". This method is based on selective sintering of powder layers with a laser beam. For each layer, the powder material (metal, polymer, ceramic or composite powders) is dispensed within a powder bed as thin layers and then scanned by laser [17].
- In 1988, the "laminated object manufacturing" method was patented by Helisys Corp. For this system, thin sheet layers are supplied to a table and a laser beam cuts the sheets through the contours of the cross section [18]. Insides of contours are stacked and bonded together by an adhesive, outsides are left as waste. Another method named "Ultrasonic object consolidation", patented by Solidica in 1999, also makes use of sheet materials as a feedstock. In this method, sheets are cut by a variety of tools (knives, drilling or milling machines, laser cutting beams, or ultrasonic cutting tool) depending on the selected material (metals and plastics) and then bonded by ultrasonic vibrations and pressure [19].
- In 1989, Scott Crump patented fused deposition modelling (FDM) technique under Stratasys Company. A movable feeding head is used to deposit the viscous-state material (any material that self-hardens and self-adheres to the previous layer such as self-hardening waxes, thermoplastic resins, molten metals, two-part epoxies, foaming plastics, and glass) at a predefined height and thickness [20]. The unique feature of this method is that it is not limited to planar sections as it can print in any direction.
- In 1989, another technique was patented in the Massachusetts Institute of Technology. This method uses a powder material feeding system similar to selective sintering. However, here the powder (ceramics, metals, polymers or composites) is bonded by a liquid binder which is selectively deposited from an ink-jet printing head [21]. Based on MIT's technology, ZCorp further developed this method and marketed AM machines which are labelled "3D printers" [22, 23]. The commercial success of the product is the reason why "3D printing" stands as a synonym for AM.
- In 1991, Solidscape patented "3-D model maker" which works in a way very similar to a 2D printing system. The liquid-phase material is deposited from the ink-jet heads drop by drop into a two dimensional plane. The layer is heated for fast solidification and then the other layer is deposited on it [24]. This technique is similar to the earlier method called ballistic particle manufacturing [25] that gained poor commercial success.
- In 1993, Arcam patented an "electron beam melting" method. As an improved version of selective sintering, this method fully melts metallic powder with an electron beam to create high-quality, durable metal components [26]. In 1996, a similar system, which works with a high energy laser beam, was developed by Meiners et al. [27] under the patent file name "Selective laser sintering at melting temperature."
- In 1999, a laser consolidation method was patented by the National Research Council of Canada. This method combines a powder material feeder with a high-energy laser beam. Powder is simultaneously melted by laser to create the layers [28]. Similar methods were invented later on, a "directed energy deposition" system by Frank Carbone in

2004 [29] and “electron beam layer manufacturing” by Scott Stecker in 2009 [30].
- In 2013, “Continuous liquid interphase printing” method was patented by Carbon Inc. This method uses photo-polymerization like in stereolithography. A major improvement is that it is aimed for mass production as it scans the cross sections in a layer-wise and continuous way [31].

Several classifications of AM methods have been published in the literature. They are mainly based on the “Step 7 - manufacturing of the physical object layer by layer” of a generic AM process mentioned earlier and also shown in Figure 2. It should be noted that proper classification of all current AM technologies may be very challenging because they may differ and also overlap in various aspects. As shown in Table 1, there are three main classifications of AM technologies in the literature:
- Guo & Leu’s material based classification
- Gardan’s method based classification
- ISO/ASTM 52900: 2015 International Standard’s classification.

In this study, AM methods are examined according to the classification presented in ISO/ASTM, as shown in Table 1. The following paragraphs explain the seven AM methods:
- Sheet lamination (SL)
- Vat photo-polymerization (VP),
- Powder bed fusion (PBF),
- Binder jetting (BJ)
- Material jetting (MJ),
- Material extrusion (ME)
- Directed energy deposition (DED).

Illustrations of processes for each one of these seven methods are presented in Figures 3, 4, and 5. The advantages and disadvantages of these AM methods are summarized in Table 2. A comparison of these seven AM methods according to “base resources” and “manufacturing process” is also given in Table 3.

Sheet lamination (SL) (Figure 3): This method uses solid planar materials (commonly papers, metals and plastics) [33]. The sheets are selectively cut (by a laser or sharp knife) contour-wise and bonded (by gluing, ultrasonic welding etc.) layer upon layer [12, 16].

Vat photo-polymerization (VP) (Figure 3): This method uses liquid photosensitive polymers called photopolymers which solidify upon electromagnetic radiation (such as gamma ray, X-ray, electron beam, UV and sometimes visible light) [16, 33]. Another synonym for the technique is “photo-solidification” as it is a

Table 1. Classification of AM methods used in AM technologies

AM TECHNOLOGIES	CLASSIFICATION		
	Guo & Leu’s Material based Classification [32]: It classifies AM techs according to the initial phase of the resource material and sets in four categories.	**Gardan’s Method based Classification [14]:** It classifies the techs according to how the resource material is processed for layering and sets in five categories.	**ISO/ASTM 52900: 2015 International Standard’s Classification [12]:** It classifies somehow both the resource material and the process in seven categories.
Laminated object manufacturing, ultrasonic object consolidation	Solid sheet	Lamination-cutting tech	Sheet lamination
Film transfer imaging (digital light processing), continuous liquid interface production, solid ground curing	Liquid	Flash tech	Vat photo-polymerization
Stereolithography	Liquid	Laser tech	Vat photo-polymerization
Selective laser sintering, sl melting, electron beam melting, direct metal laser sintering	Powder	Laser tech	Powder bed fusion
Three-dimensional printing, prometal	Powder	Jet tech	Binder jetting
Multi-jet modelling, rapid freeze prototyping, liquid metal jetting, ballistic particle manufacturing	Liquid	Jet tech	Material jetting
Fused deposition modelling, robocasting, freeze-form extrusion fabrication, dough deposition modelling, 3d glass printing	Filament/paste	Extrusion tech	Material extrusion
Laser metal deposition, laser engineered net shaping, electron beam freeform fabrication, laser consolidation	Powder	Extrusion tech	Directed energy deposition

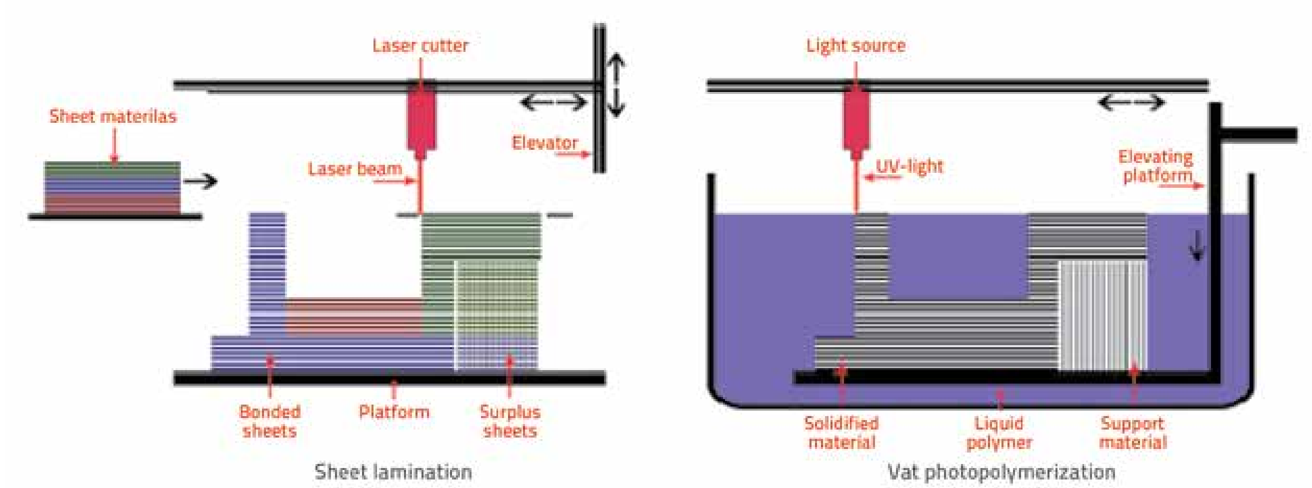

Figure 3. Illustrations of exemplary processes: SL-Sheet Lamination (left), VP-Vat-Photopolymerization (right)

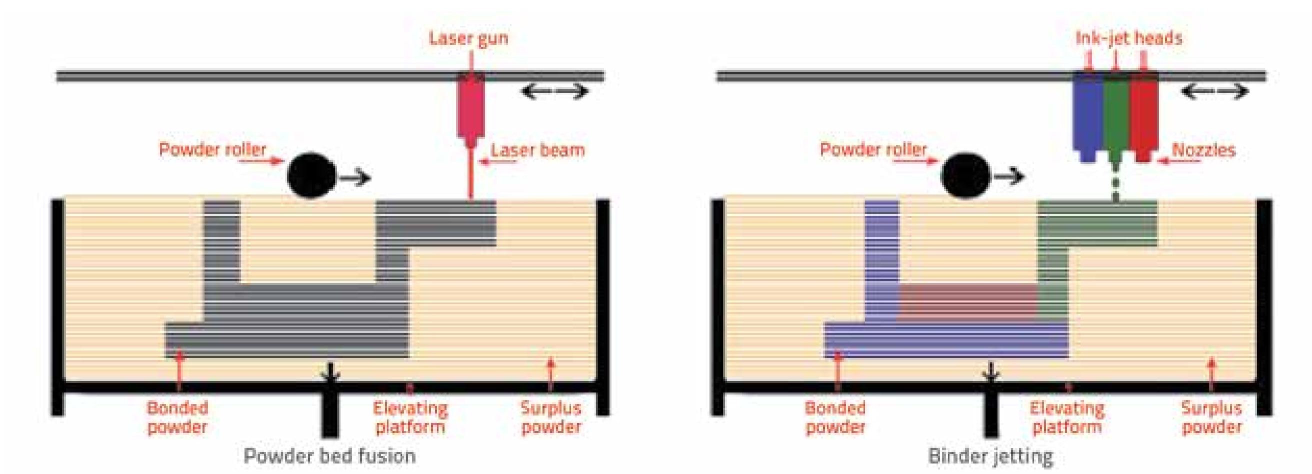

Figure 4. Illustrations of exemplary processes: PBF - Powder Bed Fusion (left), BJ - Binder Jetting (right)

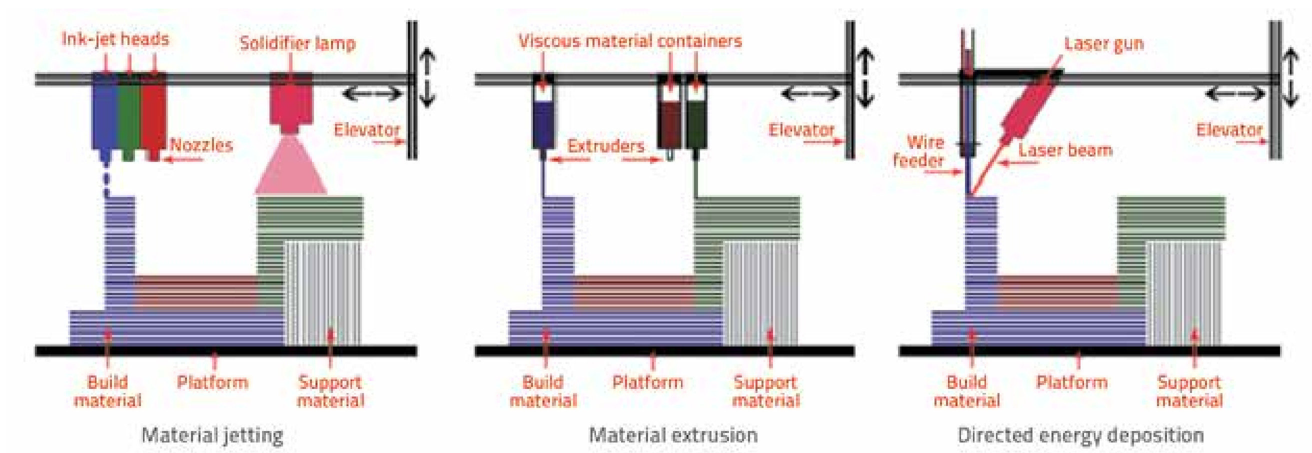

Figure 5. Illustrations of exemplary processes: MJ - Material Jetting (left), ME - Material Extrusion (middle), DED - Directed Energy Deposition (right)

Table 2. Advantages and disadvantages of AM methods [12, 16, 33]

AM methods	Advantages	Disadvantages
SL	The printing process is relatively fast since cross-sections are created by cutting through contours. Materials are inexpensive and easy to handle.	Material range is limited as it uses only sheet materials. Structural properties may be poor depending on the bonding method.
VP	Product resolution is very high providing smooth surfaces. Process is relatively fast.	Materials are very limited and expensive making the process relatively costly. Supporting elements may be needed during production.
PBF	A broad range of materials are available to choose from. No supporting elements are required during the process since the surrounding powder supports the printed layers. As the process is self-supportive, complex geometries can easily be created.	Product resolution may be poor depending on the grain size of the powder. Process is energy intensive and relatively slow.
BJ	A wide range of materials (metals, plastics, ceramics, composites) can be used. The process is relatively fast and cost-efficient. No supporting elements are required, and complex geometries can easily be created. The liquid binder increases the variety, because different combinations of powder and binder can provide various kinds of compositions with different colours and properties. Also, the printing nozzle is scalable.	Product resolution may be poor depending on the powder grain size. An important drawback is that fusing by liquid binder results in a porous composition with low structural properties, and so an additional post-processing is required costing more time and money for a better strength value.
MJ	Printing process is fast and inexpensive. Printing accuracy is good, but lower than the laser methods especially for large printings. Also, different printing compositions are possible using multiple nozzles and materials. The printing nozzle is scalable.	The material range is very limited for now as only polymers and waxes are used. Supporting elements are usually needed.
ME	The process is inexpensive. The material range is very broad. The printing nozzle is scalable.	Nozzle radius is a limiting factor. If the radius is larger, the resolution is lower. If the radius is smaller, the printing speed is lower. Supporting elements are required for complex geometries.
DED	Ability to control micro-structure of the printing area is very high. Also, the printing is not limited to a homogenous result; different compositions can be obtained by changing the material resource and beam parameters.	Material range is limited. Also, the beam radius is a limiting factor. If the radius is larger, the resolution is lower. If the radius is smaller, the printing speed is lower. The process is energy intensive.

Table 3. Comparison of AM methods according to "base resources" and "manufacturing process"

AM methods	**Base resource** (Material phase and typical materials)	**Manufacturing process** (Layering method and binding agents)
SL	Solids sheets of papers, metals, plastics etc.	Sheet feeding & contour-wise cutting (laser/knife) and lamination (adhesive/welding)
VP	Liquids of photo-curable polymers	Photo-polymerization by EMR scanning
PBF	Powders of metals, ceramics, polymers, composites	Material layering by a powder roller & sintering/melting by EMR heater or heating bead
BJ	Powders of metals, ceramics, polymers, composites	Material layering by a powder roller & adhesive deposition by ink-jet heads
MJ	Any easily solidifiable liquid (commonly resins and waxes)	Material deposition by ink-jet heads & solidification
ME	Any self-hardening viscous or molten material	Material deposition by an extruding head
DED	Any powder or wire material (commonly metals)	Material deposition by a feeder & sintering/melting by an EMR heater

process of layer-by-layer photo-polymerization. The process is performed by selectively scanning the liquid in a vat by an electromagnetic radiation (EMR) source to create each cross-section [12].

Powder bed fusion (PBF) (Figure 4): This method can use any kind of granular material such as powder of metals, plastics, ceramics, and composites. The process is performed within a powder bed [16]. For each cross-section, the material is spread over the bed as a thin layer and then selectively sintered or melted by a high-energy EMR-source (mostly by laser or electron beam) which provides the thermal energy needed to fuse the granules together [12, 33].

Binder jetting (BJ) (Figure 4): This method is similar to PBF. The process is performed within a powder bed and also any kind of powder can be used for it. The difference is that the BJ fuses the granular material together by a chemical binding agent [12]. The liquid binder is selectively deposited in drops from ink-jet heads over the powder layer to create the cross-section [16, 33].

Material jetting (MJ) (Figure 5): This method uses easily solidifiable liquid materials (commonly resins and waxes) according to an approach similar to ink-jet 2D printing [16]. The process is performed by selectively depositing droplets from ink-jet heads layer upon layer [12, 33]. After deposition of droplets, an additional phase (such as cooling or photo-polymerization) may be applied for faster and controlled solidification.

Material extrusion (ME) (Figure 5): This method can use any material being in viscous state or molten into viscous state [16]. The process is performed by selectively depositing the self-hardening viscous material through a die at constant pressure [12, 33].

Directed energy deposition (DED) (Figure 5): This method uses granular materials or filaments (commonly metal powders and

Table 4. Some prominent applications of AC in the construction industry

Applications of AC	Definition
Minibuilders (Spain)	Mini concrete extruding mobile robots which were developed in Institute of Advanced Architecture of Catalonia in 2013.
3D Concrete Printing (Netherlands)	A concrete extruding gantry system which is adapted by contour crafting in Eindhoven University.
Totalkustom (US)	A concrete extruding gantry system called Stroybot which printed a mini castle (2014) and a 130 m^2 hotel suite in Philippines (2015)
Winsun (China)	A concrete extruding gantry system which printed 10 mini houses in 2014, a mansion and a 5-storey building in China (2015), as well as an office building in Dubai (2016)
Apis Cor (Russia)	A polar concrete extruding robotic arm which printed a 38 m^2 house in Moscow (2017)
XtreeE (France)	A concrete extruding robotic arm which printed some elements (walls and columns) of YRYS Concept House in 2017
3DPrinthuset (Denmark)	A concrete extruding gantry system called BOD (Building on Demand) which printed a small office hotel in Copenhagen (2017)
CyBe Construction (Netherlands, Italy)	A mobile (wheeled) concrete extruding robotic arm which printed the R&Drone Laboratory in Dubai (2017), a 100 m^2 house in Milano (2018) and a footbridge in Netherlands (2018)
Cazza Construction (US)	A mobile (wheeled) concrete extruding robotic arm
Betabram (Slovenia)	A concrete extruding gantry system
Batiprint (France)	A Batiprint3D robotic arm which extrudes three wall-layers (two layers of insulating polyurethane as a formwork and a concrete layer in the middle). This system printed a 95 m^2 house in Nantes (2018)
Imprimere AG (Switzerland)	A concrete extruding gantry system
WASP (Italy)	A gantry type material extruding system called BigDelta which is designed to print with local terrain materials (such as clay and straw blends) and cements
Constructions-3D (France)	A mobile (wheeled) concrete extruding robotic arm
DUS Architects (Netherlands)	A plastic extruding printer-cabin called KamerMaker which printed the Canal House in Amsterdam
MX3D (Netherlands)	A mobile (wheeled) additive welding robotic arm which utilizes metals such as steel, stainless steel, aluminium, bronze or copper. The system was demonstrated by printing a bridge in Amsterdam.
ETH 3D Sand Printer (Switzerland)	A gantry type large-scale binder jetting system which prints moulds from sand material. The moulds are then filled by spraying a cementitious material. The system printed the ceiling components of DFAB House in 2018.
FreeFAB Wax (Australia)	A robotic arm which extrudes plastic wax to create moulds for concrete panels. The wax can be melted and reused for another printing.
Emerging Objects	An independent research group which experiments with a variety of powder materials such as clay, salt, cement and plastics. The powder materials are bound by a gantry-type binder jetting system to create architectural objects.
Branch Technology/C-Fab (USA)	A robotic arm which extrudes a plastic mesh that can be used as a structure on its own or as reinforcement mesh of a concrete structure. This system printed a 6.1m high pavilion structure demonstrated in Nashville.
Digital Construction Platform (USA)	A wheeled robotic arm that can extrude insulative formworks from polymers.
Arup case	A customised unique steel node was developed and printed by a gantry-type PBF system.
Skanska case (UK)	A polymer cladding element of complex geometry was printed in a gantry-type PBF system for the Bevis Marks Building.

wires) that can be easily heated and controlled [16]. The process is performed by selectively fusing the material right upon its deposition by melting it with a "focused thermal energy" which is a laser, an electron beam, or a plasma arc [12, 33]. The method is mostly used on an existing object for repairing or adding extra features [16].

2.2. Additive manufacturing (AM) methods in construction

Over time, initial primitive AM methods evolved into decent technologies that can produce multi-material and fully-functional components. Besides improvements in accuracy, speed and output quality, another aspect of progress is the printing scale. The large-scale printing methods are fundamentally up-scaled versions of the desktop-scale methods and this upscaling is a necessity for the industries like construction. For the field of construction, various terms are encountered in the literature that refer to AM. Printing objects roughly above one cubic meter in volume is referred to as "large-scale AM" [18] or popularly as "large-scale 3D printing." Construction is indeed a process of building large-scale structures and can therefore be associated with large-scale AM. Moreover, some terms are used specifically for construction industry. Some of them are additive construction, construction scale 3D printing, 3D construction printing, and construction-scale additive manufacturing. Though there is no consensus on which one to use, the term "additive construction (AC)" will be preferred in this study when referring to the field of construction. Major patents on AC and their main features are presented below [34, 35]:

- In 1995, Behrokh Khoshnevis patented the first construction-scale AM method called "Contour Crafting" (CC) at the University of Southern California. The system is hanged on a gantry structure and extrudes a viscous-state material (preferably a cementitious one) through a depositing head which is followed by a trowel to shape the layer [36]. This system can print large-scale vertical elements very quickly. The system was funded by NASA to print extraterrestrial bases.
- In 2005, Enrico Dini, who founded D-Shape company, patented a method similar to the method proposed by ZCorps. Granular material is dispensed in an enclosed structure and each layer is selectively bonded by epoxy binder spraying nozzles hanging from a gantry [37]. In 2007, Dini patented the method in which he replaced the epoxy binder with a magnesium-based inorganic binder for both ecological and mechanical reasons [38]. D-Shape's method

Table 5. Main features of AC applications in the construction industry in terms of AM method, printing material, printing mechanism, and product type [41-46]

AM method	AC applications	Printing material	Printing mechanism	Common printing products
SL	-	-	-	-
VP	-	-	-	-
PBF	Arup case	Metal powder	Gantry	Structural components
	Skanska case	Polymer powder		Cladding components
BJ	ETH 3D Sand Printer	Terrain powder	Gantry	Moulds for concrete Structural components
	Emerging Objects	Experimental materials		Ornamental and experimental structures
MJ	-	-	-	-
ME	3D Concrete Printing, Totalkustom Winsun, Betabram, WASP, Imprimere AG, 3DPrinthuset	Processed terrain mixes (aggregates, clay, cements, ceramics, etc.)	Gantry	Large-scale structural surfaces
	CyBe Construction, Cazza Construction, Constructions-3D		Wheeled robotic arm	
	Apis Cor, XtreeE		Portable robotic arm	
	Minibuilders		Mobile mini-robots	
	KamerMaker/ DUS Arch.	Polymers	Polymers	Structures and partitions
	Branch Technology		Portable robotic arm	Meshworks
	Batiprint			Insulative formworks
	FreeFAB Wax			Moulds for concrete
	Digital Cons Platform		Wheeled robotic arm	Insulative formworks
DED	MX3D	Metals	Portable robotic arm	Structural buildings and systems

is able to create stone-like monolithic structures with any complex geometry. The system was demonstrated in 2008 by printing the Radiolaria Pavilion. In addition, it printed a footbridge for Madrid in 2016. D-Shape was tested by the European Space Agency to print lunar bases.
- In 2011, a group of researchers led by Richard Buswell in Loughborough University patented a "Concrete Printing" system which is very similar to FDM whose patent expired in 2009. This method utilizes the extrusion of a cementitious material by a robotic arm. Unlike CC, this system also prints a support material and thus can create freeform structures [39].

For construction industry, Bos et al. [40] claim the year 2012 as a turning point in which a number of developments in AC started to boom.
Some prominent applications of AC are presented in Table 4. Main features of these AC applications in the construction industry in terms of AM method, printing material, printing mechanism, and product type, are also described in Table 5.

3. Discussion on the applicability of additive construction (AC) technologies in terms of use of AM methods and materials

As illustrated in Figure 6, additive construction (AC) can be divided into three main groups based on seven above-mentioned AM methods:
- AC with a material batch
- AC with a material pool
- AC with a material depositor.

Additive construction with a material batch (Figure 6): The SL (sheet lamination) is the only AM method fitting into this group. The main drawback of this method is that the complexity of the process increases with each additional component. The printing process based on this method may be very wasteful on a construction scale. Also, to print a whole building by large sectional layers would be very hard to handle. Even if it were done as component-wise, managing of the printing process would become complicated and time consuming as the number of the elements increases by each additional split. Moreover, lamination techniques for this AM method are not suitable for structural purposes when using adhesives, which usually results in components with poor structural strength, although ultrasonic welding may be an option for printing metal-made structural components.
Additive construction with a material pool (Figure 6): VP (vat photo-polymerization), PBF (powder bed fusion) and BJ (binder jetting) fit into this group. Using a material pool for a construction-scale production is a challenging method in terms of scalability, because the size of the pool is a limiting factor. This group of AC methods can be utilized for the production of customized components. Nonetheless, component-wise production can also be problematic when the assembly process becomes complicated. The VP method seems to be the least convenient one as it requires a material pool filled with a liquid resource which would be hard to handle on the construction scale. Due to high accuracy and relatively good speed of the process, another important drawback for the VP may be the high cost of photopolymers that are also not durable enough for construction. According to research made by the authors and Labonnote et al. [47], no applied developments have so far been made for this type of printing. PBF and BJ methods have similar advantages and disadvantages. These AM methods also require a material pool but filled with powder which is easier to handle than liquid. Nevertheless, the need for a powder pool on a large-scale still remains a major problem. On the other hand, this powder pool supports the printed structure until it is removed. This is very advantageous particularly for printing freeform structures that might need a support when other methods are used. Both PBF and BJ methods can utilize a broad range of powder materials with varying parameters such as cost, durability, density, grain size, etc. The use of powder results in lower accuracy compared to the use of liquids. The accuracy is even considerably lower with higher grain sizes yet, on the plus side, the speed increases. The PBF creates homogeneous and durable compositions that are suitable for structural components, although the energy-intensive process may result in high expenses. The BJ process

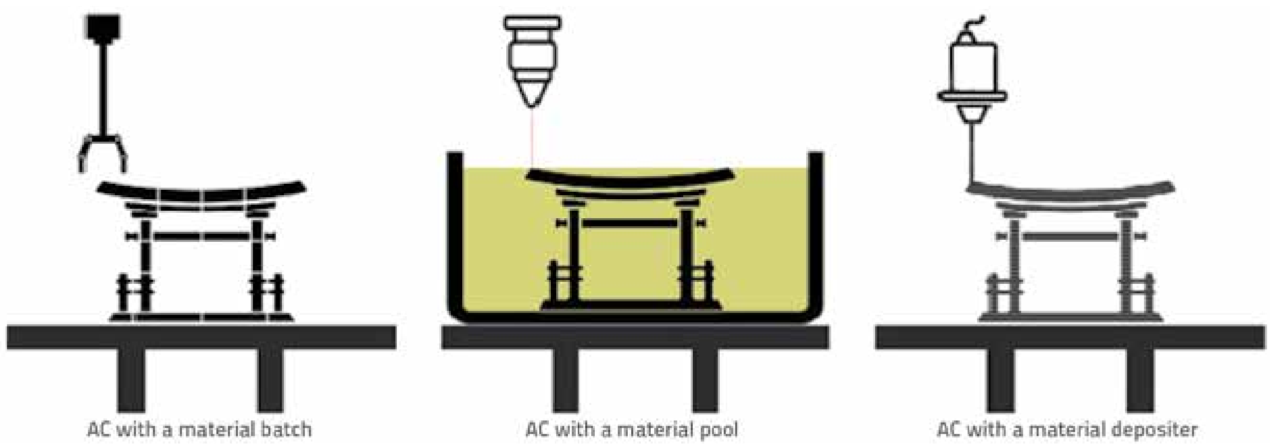

Figure 6. Additive construction: AC with a material batch (left), AC with a material pool (middle), AC with a material depositor (right)

is relatively inexpensive but it results in porous composition with poorer mechanical properties. It also has the capability of printing varying compositions by using different binders.

Additive construction with a material depositor (Figure 6): MJ (material jetting), ME (material extrusion) and DED (directed energy deposition) fit into this group. Here the scalability is less problematic because it does not require a material bed that would be prohibitive for large-scale constructions. There is a tendency to switch from heavy fixed-position gantry systems to mobile or portable printers in this field, since these kinds of robots can print structures larger than themselves. Thus, these AM methods are suitable for printing large-scale elements of the building such as walls, floors, columns, and beams. Additionally, they may also be applied over freeform surfaces such as on supportive shells, rather than on flat surfaces only. The ME method can be applied with almost any viscous-state material or with any solid that can be melted into viscous-state. It therefore provides a broad range of material options when printing a building. The die of the extruder is also scalable. Up-scaling of the extrusion-die gives rougher layering surfaces, but the process becomes faster. The MJ technology uses a liquid material that is difficult to control in large-scale constructions. Also, common materials such as waxes and photo-curable polymers are relatively expensive and fragile for building constructions based on this technique. The DED method is initially thought to be suitable for coating an existing structure rather than building it. This method is not limited to horizontal layering and can print in any axis. This feature is beneficial for creating freeform structures, but it proceeds slower. Moreover, the process of fully melting the material can produce durable composition, but at a high energy cost.

Wu et al. [41] state that main challenges to be overcome to ensure broader availability of the AM technology on the construction-scale are the scale of the product and the variety of convenient printing materials. Experimenting with cable-driven robots on a construction-scale, Barnett & Gosselin [48] state that a 3D printing material should be "inexpensive, lightweight, and storable in a ready-to-deposit state." Experimenting with aerial 3D printing by material extrusion through flying robots, Hunt et al. [49] point out that basic characteristics of a printing material should be the "density of printing material, curing time, material strength after solidification, expansion of material after curing, and cost." The same mechanisms and materials used for desktop-scale printing cannot be directly applied to large-scale printing. The materials used in AC applications are discussed in more detail below.

The local soil materials (which are also called earth-based materials or regolith for extraterrestrial construction) such as clay, sand, and rocks are the most prominent option for large-scale 3D-printing. The soil can be gathered as raw material including large elements, or can roughly be extracted as granular material. The material can then be directly sintered/melted or sintered/melted in a container for extrusion (like in additive regolith manufacturing) or chemically bonded (like in D-Shape's system). The soil materials can also be further processed into ceramics, glass or cements. Ceramics and glass are not common in large-scale printing applications for now, yet the unique capabilities of AM may evolve to such an extent that these materials can be utilised more effectively than traditional methods in the future. Cementitious materials are the most preferred resource in AC because cements are globally available and can also have satisfactory structural properties [40, 47]. Furthermore, cements have already been highly researched in the industry, and they can be prepared as an extrudable viscous-state composition that can also contain additives such as fibres and insulators. The Portland cement is also a typical material for AC, and there is a tendency to prefer fly-ash and slag containing geopolymers as they are a more sustainable option with a lower carbon footprint [44]. In most cases, soil materials (mostly cements) are extruded on-site to print the internal and external surfaces of the building. Alternatively, these surfaces are in some cases off-site printed as component-wise by binder jetting of terrain powders. While the first option seems better at printing large-scale monolithic objects (like in Apis Cor or CyBe), the second option is better at printing components with highly efficient complex geometries (like in ETH 3D Sand Printer). Solid surfaces, which serve as structural core, are printed so as to contain the voids for mechanical and electrical systems inside. After the printing, they are further processed by insulating, cladding, and integrating of other components (such as service systems, pipes and fenestrations). There are also some drawbacks of these soil/terrain materials. Despite their robustness and good compression strength, they usually perform poorly with regard tensile forces, which is why they must be reinforced. Reinforcing bars are a usual option for such reinforcement. Also, horizontal elements can be printed either as self-supportive geometries (such as catenary) or as geometries supported by other elements (such as by a temporary shell or by the surplus powder of the powder bed). As to some other downsides of these materials, they are relatively dense resulting in heavy structures and in transport-related difficulties. The high density is also a problem when printing because the material should not collapse under its own weight until it cures and gains its expected mechanical properties [48]. Yet another drawback is that they are not homogeneous unless well processed. In addition, they can not last for a long time in ready-to-use viscous state due to solidification that lasts no more than few hours.

Contrary to the use of soil materials, both Barnett & Gosselin [48] and Hunt et al. [49] recommend the use of a synthetic material (they both used polyurethane foam which can expand when released) as a solid option. Polymers can be created to exhibit various specific properties such as plasticity, opacity, strength, or chemical resistance. They can be used for a variety of purposes. Firstly, they can be printed as the main product such as components and systems. In this sense, polymers are not commonly used as the main structure, except on some exhibition projects (such as Kamermaker which prints structures by extruding polypropylene). They are much more often used as non-load bearing elements such as decorative walls and ceilings. Secondly, polymers can be printed to supplement other products. For instance, they may serve as a reinforcement meshwork (like in Branch Tech), as a mould for other materials (like in FreeFAB Wax) or as a permanent formwork that also acts as an insulation (like in Batiprint). The insulating polymers are also used as insulation for filling the voids of other structures (such as the insulation gap of a 3D-printed concrete shell). Polymers can be utilized in various forms. In most cases, polymers are preferred in their viscous-state for extrusion, because they are easy to shape due to their plasticity and they do not require a lot of energy to be melted into this state. They can be used as powders (like in Emerging Objects and Skanska case) to create components. Solid sheets are also an option, although they are not preferred for AC due to their waste. Though there is no existing application yet, their liquid-state is promising with MJ since it might be used to print various kinds of interior and exterior claddings (for instance, translucent surfaces). It might be expected that various kinds of polymers will be developed for this purpose in the future.

Metals are a commonly used resource in building construction. They are lightweight and are characterised by high structural strength. Various alloys with various properties can be created by combining several metals. Moreover, metals can be utilized in almost any form: as powders, in molten form, or as sheets. Nevertheless, metals are mostly used in the construction industry in the mass production of prefabricated building components. Generally, the AM of metals did not attract much interest in construction compared to other industries, automotive and aerospace industries in particular. For large-scale printing, metals may be costly and may also require an energy-intensive process due to their high melting temperature. For thas reason, the extrusion or deposition of molten metal for an on-site construction would be more challenging compared to cements and polymers for which cold process is used. If metal powder is used, the methods utilising a powder bed (PBF or BJ) are limited in scale, although they can be used for component

Table 6. Factors affecting applicability of AM methods on construction scale

Factors	AC with material batch	AC with material pool			AC with material depositor		
	SL	VP	PBF	BJ	MJ	ME	DED
Method scalability	Possible by portable and mobile robots	Limited to the size of material pool			Possible by portable and mobile robots		
Availability of low-cost materials	Various sheet materials	Limited to costly photo-polymers	Broad variety of discrete materials	Broad variety of discrete materials	Limited to solidifiable liquids	Broad variety of viscous materials	Limited to metals and ceramics
Processing expense	Low, yet wasteful	Low, yet requires pool structure	Energy intensive + pool structure	Low, yet requires pool structure	Low, yet requires molten material	Low, yet requires semi- molten material	Energy intensive process
Availability of durable materials	Various sheet materials	Limited to fragile photo polymers	Broad variety of discrete materials	Broad variety of discrete materials	Possible, yet requires further advancements	Broad variety of viscous materials	Possible by metals and ceramics
Composition durability	Poor when glued, better when welded	Homogeneous yet brittle compositions	Highly durable compositions	Porous compositions	Brittle compositions	Anisotropic compositions	Highly durable compositions
Material controllability	Easy to handle solids, yet might be harder when in an unstructured environment	Required amount of material is challenging, yet easier to handle since in a structured environment			Might be challenging with powders and molten materials, also even harder when in an unstructured environment		
Self-supportiveness	Not required, yet requires waste cleaning	Might be required	Not required		Might be required		Not required when well processed

manufacturing (like in Arup's metal nodes production case). DED (like in MX3D) seems to be a solid option for metals in construction since it can print powders (or wires) and is also not limited in scale. Ultrasonic welding may be an option for creating small-scale durable components from metal sheets.

In addition to the above-mentioned materials, some other materials have also been researched, experimented on and applied in desktop-scale AM. High-performance materials (such as aerogels, nano-fibre composites, graphene), smart and multi-functional materials (energy generating, opacity changing), and programmable matters (which allows 4D printing), are some of them. For now, these kinds of materials are not common to AC, yet it might be expected that they will be used for printing more functional and more efficient building elements in the future.

Based on the above discussion, the factors affecting the applicability of the AM methods on the construction scale can be listed as follows (see also Table 6):

Method scalability: The scalability is mainly determined by the mechanism (gantry, wheeled, portable) of the method. While SL, MJ, ME and DED methods can build products larger than the mechanism by mobile and portable robots, VP, PBF and BJ are limited to the size of the material pool.

Availability of low-cost materials and processing expense: SL, PBF, BJ and ME can utilize a broad range of materials. SL leads to a wasteful process on the large-scale. PBF and BJ have expenses for the material pool structure and the process of PBF is also energy-intensive. ME uses semi-molten (viscous) materials which may be costly for materials with the high melting temperature point. VP uses expensive photo-polymers and it also requires a material pool. For the time being, MJ is very limited in material range and it requires fully-molten materials. DED utilizes materials with a very high melting temperature, leading to an energy-intensive process.

Availability of durable materials and composition durability: PBF can utilize a broad range of materials and also produce highly durable compositions. BJ and ME are also broad in material range. BJ results in porous compositions, yet this composition can be enhanced by post-processing. ME results in anisotropic compositions which can be enhanced by reinforcement. DED is limited to metals and ceramics, yet it can create highly durable compositions out of them. VP and MJ create brittle compositions; they are also limited in material range. MJ is promising for the future since its material range can be expanded and it can also print multi-materials to enhance the composition. For SL, ultrasonic-welding of metals may be an option with regard to durability.

Material controllability and self-supportiveness of the method: The accuracy and speed depend on these two aspects. The first one affects the ease of controlling the material, and the self-supportiveness eliminates an additional process for supporting. Although the assembly and SL work with easily controllable solid elements, an unstructured construction environment may be a challenging factor. SL does not require supporting, yet the cleaning of waste is necessary. Unstructured environment may also be problematic for ME, MJ and DED. Furthermore, these methods may require supporting for challenging geometries and they print semi- or fully molten materials which are harder to handle compared to solids. For VP, PBF and BJ, the amount of material to fill the material pool may be challenging, yet they process inside a supportive structured system.

4. Conclusion

AC is analysed in this study in terms of applicability of AM methods and materials. Based on the findings, the following conclusions can be reached:

- For AC applications, the scalability is a crucial aspect and the tendency to switch from the gantry systems to the mobile and portable systems can be regarded as a sign of it. In terms of this aspect, "AC with a material batch" and "AC with a material depositor" are the most promising possibilities. While the first one is convenient for the assembly of mass-produced prefabricated components such as fenestrations and panels whose production would be challenging or unfeasible on the construction site, the second one is better for on-site production of custom-made building elements (such as structures, vertical and horizontal surfaces) by printing out the materials. "AC with a material pool" is limited in scale and therefore more commonly used for printing components rather than the entire building.
- Broader range of available materials means that a method can be more flexible in fulfilling a range of requirements. VP, MJ and DED are very inflexible in this sense, yet they may be utilized for specific purposes. For instance, DED is suitable for printing durable metal elements and MJ may be viable for printing functional claddings. SL, PBF, BJ, and ME can be used for almost any kind of material and thus enable printing of durable and cost-efficient materials, though they differentiate in the way the material is processed. PBF and BJ are limited in scalability, yet they can be used for component manufacturing. SL is scalable but the process is wasteful. ME is good both in scalability and material controllability.
- In terms of materials, the utilization of soil materials (mostly cements on the Earth and regolith for extraterrestrial missions) is in the foreground due to their local availability, cost-efficiency and durability. These properties make them a prominent resource for on-site printing of large-scale structural surfaces. So far, metals and polymers have not been as common as cements for AC, yet these materials have promising capabilities that have already been widely utilized by traditional means. They can be used either solely to print lightweight structures, partitions and surfaces, or to supplement other structures (usually the printed terrain-based cores) such as by reinforcing, supporting, and cladding. Moreover, there are some advanced materials that are experimented with on the desktop-scale, such as nano-engineered materials and composites that are very likely to find application in AC.
- It can generally be stated with regard to existing applications that AC is mainly focused on on-site extrusion of cementitious

materials for large-scale structural surfaces that serve as the main core of the building containing voids for insulation and mechanical & electrical systems. This approach is quite logical since the method is scalable and the material is durable, cost-efficient, and easily controllable. There are also initial signs of using metals to print structural systems and components by the PBF and DED methods, which can make full use of mechanical properties of the material. In addition, polymers are printed by extrusion to create exhibition structures, non-load bearing building surfaces, and also supplementary elements for insulating, moulding, and reinforcement meshing.

- Last but not least, it should be noted that the development of AC depends on the capabilities of robotic devices since they are the process actuators determining the quality of the outcome. Therefore, the advancements in robotics and computer systems are important for making significantly progress in AC applications.

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