Printing Architecture

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Printing Architecture

An Overview of Existing and Promising Additive
Manufacturing Methods and Their Application in the
Building Industry

REMCO VAN WOENSEL, TEUN VAN OIRSCHOT, MATS BURGMANS, MASI MOHAMMADI, AND KRISTEL HERMANS

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Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry

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Abstract: Additive Manufacturing (AM) is an emerging technology, already used in different fields. The ability to create complex, large-scale components without expensive molds and much labor makes it an interesting technology. However, the application in building construction is still in its research and development phase. This article will therefore compare and explain the state-of-the-art AM methods and investigate their possibilities in the building industry. After conducting a literature study, a distinction can be made between larger-scale and smaller-scale AM methods. The large-scale methods have been developed mostly for load-bearing prefabricated components and on-site building construction. Smaller-scale methods with a smaller layer thickness have proven to be effective at printing detailed and complex building components and objects such as façade elements and joints. These methods are, however, often limited in their materials, requiring further development. In the near future, AM is expected to complement existing building construction techniques by making objects otherwise more difficult or inefficient to create. These include, for example, double-curved walls/components, structural elements that have been designed by topological optimization, and functionally graded materials. In the future, AM could possibly be used as a full on-site building construction technique, printing entire buildings that suit our functional requirements.

Keywords: Additive Manufacturing, Building Construction, 3D Printing

Introduction

Though there have been several recent innovations in the building industry, many of the methods used in the construction of buildings are still decades old. Traditional construction techniques are still generally slow, expensive, and energy-intensive, with relatively high health risks. Building construction is also the industry with the largest number of worker deaths, representing 19.4 percent of all fatal injuries (US Bureau of Labor Statistics 2015). In addition, building engineers are often limited in their architectural and structural freedom due to restrictions by conventional techniques. The ability to create custom, complex, and freeform designs such as geometries created with topology optimization is often economically inefficient.

Additive Manufacturing (AM), which is commonly referred to as 3D printing, is an upcoming technology with the potential to fulfill these demands and change the way buildings are constructed. The American Society for Testing and Materials (ASTM) defines Additive Manufacturing as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM International 2010, 2). AM thus builds up 3D elements from layers of base material, instead of removing or cutting material out of a larger block, hence saving material and tools. Additive Manufacturing has been in development over the last forty years, since the first AM process by Ciraud in 1972 (Bourell et al. 2009). Since then, different developments have taken place that resulted in new

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AM methodologies and processes with different materials being commercialized and applied in different fields such as aerospace, automotive, and medicine.

However, the application of AM in the building industry is relatively new and is still in an early stage of development. Pegna (1997) was one of the first to suggest the use of AM in making large structures for the construction industry. He developed a process called Selective Aggregation (SA), which was intended for solid freeform fabrication of parts over 1m in size. The manufactured structures had a similar compressive strength as regular concrete structures, but the tensile strength had been drastically improved. Another advantage of SA was that it produced almost no waste, since the unused material was recyclable. This made it a more sustainable construction method. Despite that, SA was not really further developed or applied.

The research by Pegna does, however, have a lot of scientific value and provided inspiration for others to develop similar AM methods to be used in building construction. Research is still being conducted to optimize certain methods or technologies and find new applications for them. Completely new methods or improved versions of older methods have been developed over the past few years and this will probably continue to happen in the near future. Due to all the different AM methods that are used and researched by different institutes and companies, it can be rather difficult to find an AM method that best suits a specific application in the building industry. Several literature studies have been conducted on AM in the building industry (Dolhan 2013; Brescegello 2015; Hager, Golonka, and Putanowicz 2016; Wu, Wang, and Wang 2016; Labonnote et al. 2016; Bos et al. 2016; Tay et al. 2017). However, these studies focused more on the current state of development in a more general way or only discussed a few methods or separate case studies.

Therefore, this article will provide a more complete overview of existing and promising AM methods and technologies, with a main focus on (possible) applications in the building industry. These vary from large-scale technologies for larger components or even entire buildings to more detailed and small-scale methods. The overview that is provided in this article makes it possible to quickly compare all the different AM methods that are used or can be used in building construction and find out which method is suitable for a certain application. This leads to the main question of this article: What are the possible applications and limitations of Additive Manufacturing in the construction of buildings?

Research Methods

To answer this question, an extensive literature study was conducted on different AM methods and technologies, with a main focus on applications that are interesting for the building industry. A schematic overview of the entire research process can be found in Figure 1.

Figure 1: Schematic Overview of the Research Process
Data Compiled by the Authors

The first step was collecting literature and information on Additive Manufacturing. This was done using different sources including books, journals, newspaper articles, and publications from

manufactures and research institutes that use AM or are conducting research on this topic. An interview was also conducted with T. Voogd in March 2016, head of marketing and innovation at the Dutch company Bruil. Bruil is currently working on the application of AM in the building industry.

This literature was then used to classify different AM methods, which was done based on the used process techniques. These methods were then critically reviewed on their relevance for the building industry by evaluating their specific characteristics and limitations. Realized and potential applications for the built environment were also used to determine this.

For all relevant AM methods, specifications were collected using the different sources. These specifications include the process properties, materials that can be fabricated, state of the starting material, possible applications in the building industry, maximum buildable volume, structural properties, printing speed, and layer height. The process properties include the specific process technique and whether or not a support structure is needed for overhanging geometries. The applications in the building industry are both realized and potential examples for which this method can be used. The maximum buildable volume is based on the largest printer that is currently available for that method. Since strength tests for each method were not conducted in the same way, the resulting values were not suitable for comparison. Instead, an indication is given whether the method can be used to fabricate load-bearing structures. The build speed for extrusion-based AM methods is specified along the horizontal axis or xy-plane (linear speed) when possible, which is important since a higher layer thickness will result in a faster production time. The build speed for the other methods is given in the vertical direction (z-axis). The layer height is an indication of the accuracy that a method can achieve.

Based on the findings and analysis of each AM method, an overview matrix was created regarding applications that are relevant for the building industry. The application domains include scale, location, material, structural, and form. This overview matrix can help in finding a suitable AM method for a certain application domain in building construction.

Overview

An overview of all found Additive Manufacturing methods that have potential in the building industry can be found in Tables 1a and 1b. The tables contain a list of specifications and can be used to classify and compare the different methods. Figure 2 shows a timeline that indicates when the different AM methods were first developed.

Figure 2: Timeline with Additive Manufacturing Methods
Data Compiled by the Authors

Table 1a: Overview of AM Methods with Potential in the Building Industry—Part 1

<i>Method</i>		<i>Process Properties</i>	<i>Manufactured Materials</i>	<i>State of Starting Material</i>
<i>CC</i>	<i>Contour Crafting</i>	Extrusion, Requires Support Structure	Concrete, Ceramics	Paste
<i>CP</i>	<i>Concrete Printing</i>	Extrusion, Re-usable Support Structure	Concrete	Paste
<i>C-Fab</i>	<i>Cellular Fabrication</i>	Extrusion, No Support Structure	Polymers	Paste
<i>3DFP</i>	<i>3D Foam Printing</i>	Extrusion, Support Structure Not Always Necessary	Polyurethane Foam (PUR)	Liquid
<i>FDM</i>	<i>Fused Deposit Modeling</i>	Extrusion, Requires Support Structure	Ceramics, Glass, Polymers	Paste
<i>FEF</i>	<i>Freeze-form Extrusion Fabrication</i>	Extrusion, Solidification by Freezing, No Support Structure	Ceramics, Metals, FGMs	Paste
<i>DS</i>	<i>D-Shape</i>	Binder Jetting, No Support Structure	Sandstone	Powder
<i>3DP</i>	<i>Three-Dimensional Printing</i>	Binder Jetting, No Support Structure	Sandstone, Ceramics, Polymers, Metals	Powder
<i>SLA</i>	<i>Stereolithography</i>	Vat Photopolymerization, Requires Support Structure	Ceramics, Polymers, Metals	Liquid
<i>MJM</i>	<i>Multi-Jet Modeling (and PolyJet)</i>	Material Jetting, Requires Support Structure	Polymers, Metals, FGMs	Liquid
<i>LOM</i>	<i>Laminated Object Manufacturing</i>	Sheet Lamination, Requires Support Structure	Ceramics, Polymers, Metals, Wood, FGMs	Solid Sheets
<i>SLS</i>	<i>Selective Laser Sintering</i>	Powder Bed Fusion, No Support Structure	Ceramics, Glass, Polymers, Metals	Powder
<i>SLM</i>	<i>Selective Laser Melting</i>	Powder Bed Fusion, No Support Structure	Ceramics, Glass, Metals	Powder
<i>EBM</i>	<i>Electron Beam Melting</i>	Powder Bed Fusion, No Support Structure	Metals	Powder
<i>LMD</i>	<i>Laser Metal Deposition</i>	Directed Energy Deposition, Support Structure Not Always Necessary	Metals, FGMs	Powder, Solid Wire

Data Compiled by the Authors

Table 1b: Overview of AM methods with Potential in the Building Industry—Part 2

<i>Application(s) in the Building Industry</i>	<i>Maximum Build Volume (m³)</i>	<i>Structural Properties</i>	<i>Printing Speed</i>	<i>Layer Height (mm)</i>
Shelter and Housing (on-site), Walls	55.7	Load-bearing, Reinforcement Possible	1.2m/min linear, 0.13m/h in z-axis	>13
Curved Cladding Panels, Structural Objects, Façade Elements	128	Load-bearing, Reinforcement Possible	5m/min linear, Long Open Time	6–25
Interior Partitions, Decorative Walls/Elements/Ceilings, Formwork	324	Not Load-bearing, Support for Concrete	0.68 kg/h	1–10
Insulating Formwork (walls), Emergency Housing	2786	Not Load-bearing	100–200mm/s linear, Fast Curing Time	10–20
Large Architectural Components, Non-standard Bricks, Structural Elements	216	Load-bearing, Strongest Polymer-based AM Process	240–350mm/s linear	0.04–0.33
Small Functionally Graded Composite and Metal Parts	0.13	Load-bearing	127–250mm/s linear	0.5–0.65
Functional Walls, Partitions, Panels, Freeform Molds	180	Load-bearing, Fiber Reinforced	6.25mm/h in z-axis	4–6
Building Decorations, Curved Formwork, Freeform Molds	8	Not Load-bearing	15–50mm/h in z-axis	0.09–0.3
Building Decorations, Casting Patterns	1.18	Not Load-bearing	10–100mm/h in z-axis	0.05–0.15
Small Detailed Multi-Material Building Objects	0.4	Not Load-bearing (fragile)	15.4mm/h in z-axis	0.016–0.03
Metal/Wooden Parts, Smart Structures	6	Load-bearing	6mm/h in z-axis, Long Post-Processing	0.05–0.3
Metal Façade Components, Construction Joints	0.15	Load-bearing	20–35mm/h in z-axis	0.1–0.2
Metal Façade Components, Façade Nodes	0.72	Load-bearing	7–8mm/h in z-axis	0.1–0.2
Complex Nodes, Metal Glazing Systems	0.04	Load-bearing	6–7mm/h in z-axis	0.1–0.5
Complex Large Parts, Reinforcement, Corrosion Protection	8.6	Load-bearing	10–40mm/s linear	0.1–1.8

Data Compiled by the Authors

The fifteen methods from Tables 1a and 1b can be classified into seven different categories based on the used process techniques (Figure 3). These process techniques and the corresponding methods are explained and discussed regarding their application in the building industry in the following sections. Finally, in the conclusion, an overview matrix will be given with relevant characteristics of each method. This way it will be easier to find the Additive Manufacturing method that best suits a certain building application.

Figure 3: Different Process Techniques and Corresponding AM Methods
Data Compiled by the Authors

Extrusion

Extrusion is currently the most commonly used process amongst all AM methods. With this technique, a material is forced out through a nozzle by applying a certain pressure. The material is still in a quasi-solid state when it is extruded out of the nozzle. The extruded layer will then bond with the previously cured layer to create a solid structure. The material state can be controlled by using a temperature difference or a chemical change like a reaction with air or the drying of a wet material (Gibson, Rosen, and Brent 2015). Presently a variety of different materials can be printed with this process. Contour Crafting, Concrete Printing, Cellular Fabrication, 3D Foam Printing, Fused Deposit Modeling, and Freeze-form Extrusion Fabrication are the relevant extrusion-based methods.

Contour Crafting

Contour Crafting (CC) is an AM technology invented by Khoshnevis (2004) from the University of Southern California and has been in development since 1998. The technology was specifically designed for on-site construction automation. The printer is therefore installed on a large overhead gantry frame (Figure 4), which can be quickly (dis)assembled (Zhang and Khoshnevis 2013). The printers are developed for structures that have to be built fast and need to be affordable, such as social housing and buildings in disaster areas (Contour Crafting 2017).

CC uses a combination of an extrusion and filling process. The extrusion nozzle uses a side and top trowel for a smoother surface and constant top finishing. Two extrusion nozzles are used, which simultaneously print the outside edges of an object or wall with 13mm high layers of concrete. After a height of around 13cm has been reached, it will serve as a mold for a cementitious filler material that will be poured inside with a third middle nozzle (Figure 4). After a curing time of one hour, the next backfilling batch will be poured. The outer layers will then become part of the (wall) construction (Khoshnevis 2004). CC also has a newer technique, which involves a third extrusion nozzle in the middle instead of pouring cement in the structure. This

way, hollow walls with a corrugated internal structure (Figure 5) can be manufactured (Zhang and Khoshnevis 2013). This could speed up the building process, save material, and possibly increase properties such as thermal conductivity.

Figures 4–5: Contour Crafting in Construction (left); Hollow Walls with Corrugated Internal Structure (right)
Zhang and Khoshnevis 2013

Developments in CC involve the use of multiple gantries and printing heads to reduce construction time and costs. A climbing gantry has been investigated to construct multi-story buildings. Metal pipes will be placed to cured layer locations around the building, which will elevate the gantry frame to a higher level (Zhang and Khoshnevis 2013). CC also allows the possibility for reinforcement, which can be applied by an automated feeding system on the same gantry as the extrusion nozzle. For hollow structures, composite fibers can be used to reinforce the concrete. Piping and electrical wires can also be implemented by making gaps during the layering process (Khoshnevis 2004).

For overhanging structures, a support structure is usually needed. This can be done with several support columns or a lintel. Supportless structures such as domes and vaults can also be achieved. For flat roofs, a robotic arm on the gantry could position beams with sheets on the printed structure, on top of which the roof or floor can be printed (Khoshnevis 2004). CC is also being investigated by NASA for its application on the moon to build dwellings in which the lunar soil will be used to mix a special printable concrete (Khoshnevis 2004).

Even though this AM technique has been under development for almost twenty years, it still has not really been applied in commercial construction automation projects and it is limited to experimenting with different wall structures and material properties. A reason for this is that traditional construction techniques are still needed besides CC for the foundation, windows, and horizontal elements. Also, detailed and complex building shapes, like double-curved buildings, are still not yet possible to produce with this method, making this method less time and cost efficient.

Other companies are also using methods similar to CC and are already printing entire structures and buildings. For example, the Chinese company Yingchuang/Winsun has a very large concrete printer that is capable of realizing entire buildings. The biggest difference is that building components are printed in a factory, before they are transported to the building site (Naboni and Paoletti 2015). Another similar example is the company Apis Cor (2017) that printed the concrete walls of a 38m² full-scale house on site.

Concrete Printing

Concrete Printing (CP) was developed in 2006 by the Freeform Construction research team at Loughborough University and uses the same extrusion-based process as the previously described Contour Crafting (Oxman et al. 2014). However, CP is designed for prefabrication of concrete

elements. A high performance material can be created by adding different kinds of materials to the concrete mixture (Burgt and Wezel 2014).

The printing process is shown in Figure 6. A 5.4x5.5x5.4m gantry is used to print layers of concrete, which limits the dimensions of the printed object. Between two layers, a specific open time (max. 15 minutes) is required to obtain an in-layer bonding with a high strength (Burgt and Wezel 2014). Also, the concrete mixture needs to be refilled every once in a while, which also increases the printing time. In order to print overhangs, gypsum is used as support material. This is easy to remove and re-usable. The layer properties have a big influence on the final product. The layer orientation is important, because the strength in the three different directions is not the same (Burgt and Wezel 2014). Also, the resulting ribbed surface finish is influenced by the used layer thickness, as the layers are visible in the final product. Like CC, the total built volume is currently limited by the gantry dimensions.

A realized example of CP is a wall-like bench (Figure 7). This product was made to show what the construction scale possibilities of CP are. The bench has a volume of 2.0x0.9x0.8m and consists of 128 layers. It is capable of bearing loads due to the use of reinforcing bars, which are placed in the gaps. These gaps are included to reduce weight, for thermal insulation and building services (Lim et al. 2012). This example clearly shows that CP provides freedom in both internal and external geometries. Loughborough University has continued to develop the method since the first design. In 2014, they were able to create a geometrical complex freeform construction. This object is also load-bearing, which demonstrates that load-bearing, complex geometries are relatively easy to obtain.

A similar technique is also used by the company Bruil (BV 2017), which has been experimenting with Concrete Printing since 2015. Their main goal is to create architectural concrete for façades with different colors in one continuous print, which cannot be produced with conventional production methods. Their current printer has a layer width of circa 4–6cm and a layer thickness between 5mm and 20mm. With this printer, they managed to develop a parametrically designed façade element (Figure 8) in February 2017. The shape and structure of the element can be varied depending on the amount of solar radiation that is required inside the building at a certain location on the façade, with more closed elements at locations where sunlight needs to be blocked and more open elements at locations where sunlight is wanted. More conventional methods would require a different mold for every element, while using a concrete printer makes it relatively easy to produce a large amount of unique façade elements. This shows that Concrete Printing has a lot of possibilities in the building industry. As T. Voogd of Bruil explained, CP can take all important building-related aspects (mechanical properties, insulation, space for building services, architectural freedom) into account during the design process to create constructions that are optimized for all these aspects.

Figures 6–8: Concrete Printing Process (left); Wall-like Bench (center); Façade Element by Bruil (right)
Le et al. 2012; Lim et al. 2012; Bruil BV 2017

Cellular Fabrications

Cellular Fabrication (C-Fab) is an extrusion-based process from Branch Technology that can print optimized composite (ABS plastic and carbon fibers) structures in an open space, instead of using a traditional layer-by-layer method. This process uses an extruder attached to a 3.8m robotic arm on a 10m long rail system, allowing the possibility of very large structures. The resulting open matrix structures will serve as support for construction materials such as (sprayed) concrete and insulation (Figure 9), essentially replacing formwork. C-Fab is developed for construction projects with unlimited design freedom, such as double-curved walls and structurally optimized structures (Branch Technology 2015). A current limitation is the slow printing speed for printing the open plastic matrix core. Also, C-Fab can currently only print indoors, requiring the components to be assembled on-site.

C-Fab is thus not used for printing the buildings itself, but is helping the current building industry achieving high design freedom without high extra costs or much labor. It therefore has more potential to be applied in the near future. This potential is shown by the freeform home design *Curve Appeal* (Figure 10) by WATG (2016), which will be built using the C-Fab method. Another C-Fab construction project is *Flotsam & Jetsam* in Miami by Shop Architects and Oak Ridge National Laboratory (BAAM machine), which is printed with a biodegradable bamboo filament.

Figures 9–10: Prototype Wall (left); *Curve Appeal Home* (right)
Branch Technology 2015; WATG 2016

3D Foam Printing

The previously discussed AM methods are used to produce materials such as concrete and plastics. Recent developments have also allowed printing of foam structures. Multiple studies have experimented with an extrusion process to produce large-scale (architectural) components. Polyurethane foam (PUR) was used as building material since it is light, adhesive, relatively inexpensive, has a fast curing time, and a high insulation value.

A study on PUR was done by The Mediated Matter group from The Massachusetts Institute of Technology (MIT), called the Print-in-Place technology (Oxman et al. 2014). A robotic arm is used to print PUR in layers as insulating formwork. Overhangs and double-curved surfaces were possible to realize without support structure due to the high adhesive properties and layer height (40mm). This thick layer also resulted in a very fast build speed. The spray foam system also allows instalment of components such as reinforcing bars, which can be seen in Figure 11

(Keating and Oxman 2013). This technique was also applied on-site to print a building-size hemisphere structure (Figure 12), using a large mobile compound arm system. This structure was printed within 13.5 hours and has a diameter of 14.6m with a variable thickness over the height of the dome. Due to the high expansion rate of the used foam, this method also outperforms other automated construction techniques in volumetric fabrication rate. Furthermore, a preliminary financial analysis showed that the costs of printing the formwork of a house with this method is 31 percent less expensive than a regular insulating concrete form wall (Keating et al. 2017).

Research has also been done by the University of Nantes to print insulated emergency housing out of PUR in a very short time. This is done with the INNOprint 3D printer, a robotic arm which is capable of printing objects of 3m in size in 30 minutes (Suire 2016).

Current limitations that need further development are the possibility of blockages in the printing head that is caused by the fast curing rate. Also, due to the large expansion of foam the surface is rough with a visible layered structure. This problem could however be solved if a conventional finishing is applied. Finally, curing issues due to the influence of moisture have been experienced during outdoor printing (Keating et al. 2017).

Figures 11–12: 3D Foam Printed Formwork with Rebars (left); Insulating Formwork Dome (right)
Keating and Oxman 2013; Keating et al. 2017

Fused Deposit Modeling

A very commonly used extrusion-based method is Fused Deposit Modeling (FDM), which was developed by Stratasys around 1991 (Strauß 2013). With FDM, the state of the material is controlled by a temperature difference. A thread of material is guided into the print-head, where the material is heated slightly above melting point. When the paste is extruded from the nozzle, it will immediately cool down, harden, and bind with the layer beneath it (Guo and Leu 2013). To improve bonding, the process usually takes place in a heated chamber (Strauß 2013). Printing in a chamber under an inert gas environment also increases the mechanical properties; however, this will limit the scalability of the printer. Due to the high popularity of this method, a lot of variants of this method exist, developed by multiple companies.

The biggest advantages of FDM are the range of materials that can be printed and the relatively high strength. FDM is mainly used to print polymer-based structures, since there is no other AM method that reaches the same mechanical properties for this type of material. It is also possible to print ceramic materials and glass with FDM (Gibson, Rosen, and Brent 2015).

Some disadvantages of FDM are that the process is rather slow and if high accuracy is required, the build speed and costs will be even higher. The reason for this slow build speed is that the process depends on how fast the print-head can melt the material. Improving this by applying more heat requires a nozzle that moves faster and this reduces the accuracy. Another disadvantage is that it is difficult to print sharp edges, which is the case for most extrusion-based methods. Due to the anisotropic way of printing, the material and mechanical properties are much better in the x- and y-direction than in the z-direction, where the layers are fused together.

Temporary support structures are needed for larger overhangs, which are usually printed with a secondary nozzle. Finally, parts that are produced with FDM will require post-processing if air and watertight objects or smooth surface finishes are desired.

A large-scale example of FDM is the 3D Print Canal House by DUS Architects that is currently in development in Amsterdam (Wolfs 2015). The 3D Print Canal House is printed on-site and is composed out of parts with a maximum size of 2.2x2.2x3.5m. After the printing is complete, the parts (Figure 13) are assembled like Lego-blocks. Each part contains hollow areas that can be filled with reinforcing (concrete) or insulating materials. The hollow areas are also used for the placement of pipes and wires. An advantage of this principle is that the building can easily be dismantled and re-assembled on a different location (Naboni and Paoletti 2015). It is also possible to print multifunctional and translucent façade elements with FDM (TUM 2017). Another application of this method in architecture is the Building Bytes project by B. Peters (DesignLab Workshop), in which independently printed ceramic bricks are used together in façades and structural elements (Naboni and Paoletti 2015). This project shows that even small 3D printers can produce functional parts for the use in the building industry (Figure 14).

Figures 13–14: Part of the 3D Print Canal House (left); Honeycomb Bricks by Building Bytes (right)
Naboni and Paoletti 2015

Freeze-form Extrusion Fabrication

Freeze-form Extrusion Fabrication (FEF) is an AM method that was developed at the Missouri University of Science and Technology (Guo and Leu 2013). FEF is another extrusion-based method, but differs from FDM since every layer of paste is solidified by freezing. The entire printer is placed inside a freezing chamber in order to keep the temperature below 0°C. Since the extruded material is solidified immediately, a support structure is usually not required. FEF can be used to produce ceramic, metal, and composite parts. A disadvantage of FEF is the possible forming of ice crystals, which can result in large voids and reduced mechanical properties. Currently, the process is still in its early research phase and the printed products are still small in size.

Advantages of FEF are that it reduces the need of an organic binder, it is environmentally friendly, and it has low equipment costs. Another benefit is that it can be used to produce functionally graded materials (FGMs) consisting of different materials (Figure 15). FGMs are materials with a variation in composition gradually over the volume of the object (Guo and Leu 2013). In the building industry, FGMs could have high potential for conserving materials and also change the way buildings will look like in the future. FEF produces FGMs by using multiple

extruders that deposit different materials simultaneously. The composition of the materials is varied by controlling the extrusion speed of every extruder separately (Guo and Leu 2013).

Figure 15: Functionally Graded Material Produced with FEF
Guo and Leu 2013

Binder Jetting

Binder jetting (BJ) is a technique that uses small liquid binder droplets that will be delivered through multiple nozzles onto a powder bed. The binder material reacts with the powder material, solidifying the powder material where the object needs to be formed. Once a cured layer is formed, a new layer of powder is spread on top of the current layer and the process is repeated. This process generally does not require any support structure as the formed parts are supported by the unreacted powder bed (Gibson, Rosen, and Brent 2015). D-Shape and Three-Dimensional Printing are the relevant methods that are based on binder jetting.

D-Shape

D-Shape (DS) is an AM method that mainly focuses on the production of large-scale constructions. The method was developed by Dini in 2004 and he has been improving it since then (Burgt and Wezel 2014). D-Shape can be used to create sandstone-like structures. Originally, it was designed to be used for off-site production, but there are already plans for the on-site production of a large estate in New York with an up-scaled printer using local materials (Wolfs 2015).

The powder bed that is used for D-Shape consists of a fine layer of granular material. A large truss structure (Figure 16) is used to deposit the liquid binder through multiple nozzles (Figure 17). Before the next powder layer is added, the current layer needs to be compressed using a roller (Lim et al. 2012).

Figures 16–17: Printing Truss Structure (left); Adding the Binder (right)
Cesaretti et al. 2014

After the printing process, additional post-processing is required. The printed construction needs to be dug out of the shell of remaining granular material (Figure 18), which can then be re-used for the next object (Burgt and Wezel 2014). The strength of the printed material differs depending on the direction of the load, but this difference is not significant (Burgt and Wezel 2014).

One of the advantages of D-Shape is that it can use local and common/inexpensive sand-like materials to create constructions. Therefore, research is currently being conducted on the use of D-Shape to print moon bases (Cesaretti et al. 2014). The lunar soil can be used as construction material and only the binder needs to be transported from earth. D-Shape also makes it possible to print entire houses in one single process (Figure 19). D-Shape is currently limited to stone structures of which the size is constrained by the gantry dimensions. Other limitations are the relatively slow speed due to the thin layers, rough exterior surfaces and a lower material strength compared to other large-scale printing techniques.

Figures 18–19: Removing Remaining Granular Material (Left); House Printed in Single Process using D-Shape (right)
Caneparo 2014; Cesaretti et al. 2014

Three-Dimensional Printing

Three-Dimensional Printing (3DP) is a powder-based AM method invented by MIT around 1993 (Gibson, Rosen, and Brent 2015). Unlike D-Shape, this method is able to print any material that is available in powder form and able to react with a liquid binder (e.g. plastic, ceramic, metal, gypsum, and cementitious powders). 3DP also deposits the powder and reacting binder automatically and is therefore a more continuous printing method. Parts can be infiltrated with an epoxy resin to increase strength, durability, and improve the surface finish. By adding a color cartridge to the print head, it is also possible to print with multiple colors (Strauß 2013). However, printed parts have a low strength and are rather brittle. They can therefore not be used in structural applications. Future studies could improve this by experimenting with different powders and additives such as steel and Fiber Reinforced Polymer composites (Feng et al. 2015).

3DP does not necessarily require a heated chamber and is therefore scalable to larger build volumes. Recently, the company Voxeljet developed a very large 3D printer (VX4000) with dimensions of 4x2x1m. This machine uses silica sand as powder material. With its ability to fabricate large objects, it has high potential in the building industry, especially for detailed structures. This has been demonstrated among others by the project Digital Grotesque from Hansmeyer and Dillenburger (Figure 20). This built structure is a large, fully enclosed, detailed and ornamented room consisting out of eighty printed sandstone components (Naboni and Paoletti 2015). Other examples include a small house by 3M FutureLAB and a living room by Brument, both created with printed molds.

Figure 20: Digital Grotesque
Naboni and Paoletti 2015

Vat Photopolymerization

The AM process vat photopolymerization (VP) uses a liquid resin of polymers that are sensitive to UV-light, also called photopolymers. This liquid resin is placed in a vat, in which a cross-section will be radiated, usually with a UV laser (Figure 21). This will cause a chemical reaction, which will solidify the radiated surface pattern to form the part. A fresh liquid resin layer will then be swept on top of the cured layer and the process will continue until the object is finished. Often the printed part is then further cured in a UV oven. To print overhangs, temporary support structures will be needed, which are generated automatically by the system (Gibson, Rosen, and Brent 2015). The most common and relevant method that uses vat photopolymerization is Stereolithography.

Figure 21: Vat Photopolymerization Process
Wolfs 2015

Stereolithography

Stereolithography (SLA) is the first commercialized AM method, invented by Hull (founder of 3D Systems) around 1987. SLA was initially used to print small parts. However, with, for example, the Mammoth printer from Materialise, parts with a length of over 2m can be printed (Strauß 2013). A new similar method that also uses vat photopolymerization is the Continuous Liquid Interface Production (CLIP) by Carbon3D. Due to the process being continuous, very high printing speeds can be achieved (Carbon3D Inc. 2015). However, the built envelope is still relatively small.

The main advantages of SLA are its high part accuracy and smooth surface finish in comparison with other AM methods (Gibson, Rosen, and Brent 2015). Also, in contrast to most other methods, the mechanical properties behave consistent in all directions (Carbon3D Inc. 2015). Applications of SLA in the building industry are currently limited to prototypes and scale models due to the high material costs and issues with resistance to UV-radiation and humidity (Strauß 2013). However, with developments in photopolymer materials, there will be more potential for the application in the building industry as relatively large objects with high accuracy could be printed in one piece. Realized examples show that fabricated structures with protective coatings can be applied outdoors. Process variations have already been developed by adding metal or ceramic powder to the curable resin to produce complex metal and ceramic parts with a smooth surface finish (Guo and Leu 2013).

Material Jetting

Similar to vat photopolymerization, material jetting (MJ) also relies on photopolymerization. This AM process however uses hundreds or thousands of small nozzles on a print-head arranged along the building platform. These nozzles dispense drops of liquid photopolymers, which are immediately cured by a UV lamp. The print-head will continue to move back and forth to deposit and cure a layer. When a layer is complete, the work platform will descend by the layer height and the next layer will be built on top of the previously cured layer (Guo and Leu 2013). Multi-Jet Modeling and PolyJet are two very similar methods that are based on material jetting.

Multi-Jet Modeling and PolyJet

Multi-Jet Modeling (MJM) and PolyJet were invented and developed by 3D Systems and Objet Geometries (now Stratasys) respectively in the mid-1990s (Strauß 2013). The difference between both technologies is that MJM uses wax as support structure, which can be removed by melting it in an oven, while PolyJet uses a gel-like material as support structure, which needs to be removed by hand or with high pressure water jetting (Gibson, Rosen, and Brent 2015). These support structures are printed with secondary nozzles. Besides polymers, it is also possible to indirectly print metal parts by using small metal particles in the used liquid, as is done in XJet's NanoParticle Jetting (XJet Ltd. 2016).

The largest build chamber up to now has a build size of 1x0.8x0.5m (Objet1000). Advantages of these methods are the very high resolution and the smooth surface that is achieved. Another important benefit is the possibility to print and mix multiple materials and colors, which enables the fabrication of "digital materials." These are composite materials with programmable predefined properties. Like FEF, this also makes it possible to print FGMs. However, developments are necessary as the current photopolymers are not very durable (Strauß 2013).

The costs of producing PolyJet parts are relatively high in comparison to other methods that use polymers. When producing the same benchmark samples, the PolyJet parts account for the highest costs, while FDM and SLS have the lowest total costs per part. However, by printing

more than one part in a single build, the costs per part will probably decrease (Li et al. 2017; T. A. Grimm & Associates Inc. 2010).

Sheet Lamination

Sheet lamination (SL) (Figure 22) is notably different from other AM techniques. It is the only process that uses solid sheets as starting material. The sheets are generally cut using a laser, either before or after bonding of the layers. The bonding of sheet layers can be done by adhesive bonding, thermal bonding, clamping, or ultrasonic welding. The portion of the sheet that is not used for the final part will serve as support structure (Gibson, Rosen, and Brent 2015). Laminated Object Manufacturing is the most common method based on sheet lamination, which will be discussed together with Ultrasonic Consolidation.

Figure 22: Sheet Lamination Process
Gibson, Rosen, and Brent 2015

Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) was invented around 1991 by Helisys (Strauß 2013), and can be used to produce parts from plastics, ceramics, metals, and paper. When using paper as starting material, the end result would be very similar to a wooden block, but a coating is required to prevent moisture absorption (Gibson, Rosen, and Brent 2015). It is a useful method for functional parts in almost every geometry when costs and operation time need to be reduced.

Subsequently, an interesting and promising recent variation of this method was developed by Solidica (now Fabrisonic). The method is called Ultrasonic Consolidation, where solid metal sheets are bonded using ultrasonic vibrations (Gibson, Rosen, and Brent 2015). This method allows for the production of large parts (1.8m) consisting of multiple materials and with complex internal features. In the building industry, potential applications are FGMs and smart structures with integrated sensors and other processors. A limitation of this method is the highly anisotropic mechanical properties of the bonded metal parts with substantial reduced strengths in the y- and z-axis (Gibson, Rosen, and Brent 2015). Also, due to the ultrasonic bonding, the final strength of the printed objects will be lower than the base material. Another limitation is that subtractive manufacturing techniques such as CNC milling are used in this method to obtain the desired geometry, resulting in more material loss.

Powder Bed Fusion

Like binder jetting, powder bed fusion (PBF) uses a powder bed as starting material. However, the liquid binder is replaced by one or multiple lasers or electron beams, which are used to solidify the

powder to create a part (Figure 23). No additional support structures are needed as the remaining (re-usable) powder will provide the necessary support. The building process normally takes place in relatively small enclosed chambers with a protected environment to minimize oxidation (Gibson, Rosen, and Brent 2015). Three relevant AM methods that use the powder bed fusion process are Selective Laser Sintering, Selective Laser Melting, and Electron Beam Melting.

Figure 23: Powder Bed Fusion Process
Frazier 2014

Selective Laser Sintering

Selective Laser Sintering (SLS) is an AM method developed by DTM in 1992, later acquired by 3D Systems. With SLS, laser beams are used to sinter the powder to solidify the object's cross-section. Sintering means partial melting of the powder below the melting point (Strauß 2013). To keep the temperature of the build chamber just below the melting point, infrared light is used. Different kinds of powder can be used to fabricate materials like polymers, ceramics, composites, and metals (Guo and Leu 2013). Also, waste powders that are created with the production of other materials can be used (Naboni and Paoletti 2015). Because SLS takes place under a protective gas environment, build chambers are often limited in size and difficult/expensive to scale up.

Application in the building industry is currently limited to smaller complex objects used in façade construction or steel construction joints. Examples are a steel joint developed by Arup (Figure 24) and polyamide sheaths by Priestman (Figure 25). The node by Arup is meant for lightweight tensile structures with custom and complex shapes. The node is based on topological optimization and should reduce CO₂ emissions and waste materials a substantial amount (Naboni and Paoletti 2015). The node sheaths by Priestman were installed on a steel joint of a rooftop canopy. SLS was used to fabricate the polyamide sheaths, because of their complex shape and unique design for each structural joint. Production with an AM method like SLS was therefore less expensive and time-consuming than with traditional methods (Naboni and Paoletti 2015).

Figures 24–25: Steel Node (left); Node Covered with Sheaths (right)
Strauß 2013; Naboni and Paoletti 2015

Selective Laser Melting

Selective Laser Melting (SLM) is deduced from SLS, but instead fully melts the powder, resulting in more dense and stronger parts. SLM is mainly used to produce metallic products. There is a small variation in alloys which can be used: stainless steel, cobalt chromium, Inconel, and titanium (Guo and Leu 2013). Research has been done by various institutes to create metallic façades. For instance, Strauß (2013) did a study on which AM method is most suitable to create a (metal) façade construction. In his report he compares, among others, SLM, SLS, and PolyJet with each other and uses criteria like architectural design and possibilities of system integration. He concludes that SLM is, in the future, the best method to create a façade construction because it can be adapted to new fields of application rapidly. Realized examples are the unique freeform façade joint by ConstructionLab in Detmold called the Nematox node (Strauß 2013), and a spider bracket designed with topological optimization (Materialise 2016) (Figures 26 and 27). The expectation is that SLM will be used for creating larger metallic components for façade construction. One of the problems, however, is the un-used metal powder that functions as a support structure, which can be hard to remove with complex geometries (Zeng et al. 2015).

Figures 26–27: Nematox Node and Spider Bracket
Strauß 2013; Materialise 2016

Electron Beam Melting

Electron Beam Melting (EBM) was first developed at the Calmers University of Technology in Sweden. The first commercialized product was brought on the market by Arcam AB in 2001 (Gibson, Rosen, and Brent 2015). The method is similar to SLS and SLM in some ways, but EBM uses an electron beam as heat source and takes place under complete vacuum since materials that are sensitive to oxygen (like titanium) are used to produce the parts. The operating temperature in this vacuum is around 1000°C (Strauß 2013). Electron beams are generally more efficient and less expensive, making this method more cost and energy efficient than SLS and SLM (Gibson, Rosen, and Brent 2015).

The final metal parts have some typical positive characteristics: they are fully dense, void-free, and extremely strong. This creates lightweight freeform structures. One negative aspect however is the fact that the resulting parts have to be post-processed because the final surface finish is less smooth than with SLM and therefore not always suitable for its application (Strauß 2013).

EBM can be used to produce multi-materials with stainless steel (Hinojos et al. 2016), indicating that façade (and possibly structural) parts for complex building applications can be created. These include for example cable-net structures, point-supported glazing systems, and unique nodes with varying forms of lattice structures (Warton, Dwivedi, and Kovacevic 2014).

An example of an EBM printed lattice assembly prototype consisting out of six different y-branch nodes is shown in Figure 28.

Figure 28: Lattice Assembly Prototype
Warton, Dwivedi, and Kovacevic 2014

Directed Energy Deposition

Similar to the methods based on powder bed fusion, directed energy deposition (DED) is mainly used to fabricate metal parts. Instead of a powder bed, the material is completely melted with a direct narrow energy source (usually a laser or electron beam) while it is being deposited through one or two feed nozzles (Figure 29) (Gibson, Rosen, and Brent 2015; Guo and Leu 2013). An AM method that uses directed energy deposition is Laser Metal Deposition.

Figure 29: Directed Energy Deposition process
Gibson, Rosen, and Brent 2015

Laser Metal Deposition

Laser Metal Deposition (LMD) was first commercialized by Optomec in 1997 and is used to create fully dense metal parts (Gibson, Rosen, and Brent 2015). Similar process variations are Direct Metal Deposition (DMD), Electron Beam Additive Manufacturing (EBAM), and Laser Engineered Net Shaping (LENS) (Guo and Leu 2013). Metal powder or solid wire can be used as feedstock when using LMD. Using a wire feedstock results in lower accuracy, reduced costs, and an increased fabrication rate compared to a powder feedstock. With LMD, the printing process can be executed in an open environment (with an inert gas surrounding the laser). This allows for larger build volumes. Because this method uses locally spraying nozzles, it can repair existing products and produce FGMs when multiple nozzles are used. Another advantage is that it can produce very thin walls, since the lasers can generate layers with a resolution of 0.1–1.8mm (Guo and Leu 2013).

One of the developments since the first commercialized LMD machine is to produce bigger products. Examples of larger LMD printers are the EBAM 300 and LENS 850-R. Present machines also already have dual wire and powder feeders. The main limitations of this method are the poor surface roughness and the expensive support structure that is usually needed for complex geometries, resulting in increased post-processing.

Laser Metal Deposition is currently not used in the building industry, but there are possibilities since large metal parts with high strengths can be manufactured. A promising example is MX3D, developed by Joris Laarman Lab. MX3D uses Wire and Arc Additive Manufacturing (WAAM) to produce constructing architecture. They are currently printing a full-scale steel bridge (Figure 30). The price of a WAAM printing cell is around 80 percent lower than a SLM printer and the base material is around ten times less expensive (MX3D BV 2017). This shows that WAAM is often more suitable for large-scale metal objects. A challenge will be to prevent the oxidation of the printed metal, as no oxygen-free chamber is being used. Originally it was planned to build the bridge on-site, but developments are required before this can be realized. Another potential application is to print reinforcement for complexly shaped structures (Naboni and Paoletti 2015).

Figure 30: MX3D Bridge under Construction
MX3D BV 2017

Conclusions and Implications

An overview has been provided of the current Additive Manufacturing methods and technologies that can be used in the building industry. Table 2 shows the most important conclusions for each method regarding its application in the building industry. They are divided into different categories: scale, location, material, structural, and form. Each method has its own advantages and specific applications that could be used in building construction.

A first distinction in AM methods can be made between large-, medium-, and small-scale methods. Here, the large-scale methods are mainly used for printing entire walls/buildings and large structural elements. Medium-scale methods are used for printing larger building components, which can be assembled together to construct buildings. The small-scale methods can print detailed objects or constructive joints. Thin-layered methods with ongoing and realized examples of large-scale structures are 3DP, FDM, and LMD. The scale of the methods also depends on the type of the used printer. Gantry systems and robotic arms are often used for large- and medium-scale methods. Other methods are often conducted in an enclosed chamber and are therefore difficult or cost-inefficient to scale up.

Table 2: Building Applications for Each Additive Manufacturing Method

		Extrusion						BJ		VP	MJ	SL	PBF			DED
		CC	CP	C-Fab	3DFP	FDM	FEF	DS	3DP	SLA	MJM	LOM	SLS	SLM	EBM	LMD
SCALE	Large-scale	✓		✓	✓			✓								✓
	Medium-scale		✓	✓		✓			✓	✓		✓				✓
	Small-scale					✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
LOCATION	On-site production	✓			✓	✓		✓								✓
	Prefabrication		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Outdoor application	✓	✓	✓	✓	✓		✓					✓	✓	✓	✓
MATERIAL	Concrete	✓	✓													
	Sandstone							✓	✓							
	Ceramics	✓				✓	✓		✓	✓		✓	✓	✓		
	Glass					✓							✓	✓		
	Polymers			✓	✓	✓			✓	✓	✓	✓	✓	✓		
	Metals						✓		✓	✓	✓	✓	✓	✓	✓	✓
	FGMs						✓				✓	✓				✓
STRUCTURAL	Load-bearing	✓	✓	✓		✓	✓	✓				✓	✓	✓	✓	✓
FORM	Double-curved objects		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
	Smooth surface finish									✓	✓					
		CC	CP	C-Fab	3DFP	FDM	FEF	DS	3DP	SLA	MJM	LOM	SLS	SLM	EBM	LMD

Data Compiled by the Authors

Secondly, a distinction can be made between on-site fabrication and prefabrication of elements. Currently, most methods print pre-fab elements. The scalability of some printers and outdoor weather conditions will make on-site AM more difficult. However, in countries like China with a different climate and housing shortage, on-site construction with a form of CC has already successfully been conducted. Experiments are also being conducted to print on-site with other methods, such as DS, 3DFP, FDM, and LMD, mainly to save on transportation and time. It also enables the possibility to use locally available materials to print structures.

Most AM methods print pre-fab complex structures or connections with freeform (double-curved) shapes that are more efficient to produce than with conventional methods. This could benefit both architectural and structural design, with for example topological optimization. This way the advantages of additive manufacturing are exploited, something that is currently not always the case for on-site printing.

In addition, the chosen method often depends on the desired material because stone-like materials can be produced by the large-scale methods and the small-scale techniques are generally producing polymers, ceramics, and metals. The number of fabricated materials is expected to increase, as currently many methods use polymers as building material. This type of material creates issues in the areas of UV-light, moisture, and fire resistance, which will reduce outdoor durability. New developments in these material properties will thus enhance the potential for building construction. Also, mechanical and thermal properties are expected to improve.

An innovative material concept for the building industry that has been mentioned is functionally graded material. This concept is studied among others by the Mediated Matter Group at MIT, who have developed printed concrete with varying densities to reduce mass. For buildings, it also has the potential to replace parts consisting of different materials. In the more distant future, buildings may even consist of a single, multifunctional body, completely replacing insulation and even windows by making some parts of the wall more translucent. Whether the printed parts can be used as load-bearing elements depends on the used material but also on the printing process. Furthermore, some methods are used in combination with conventional

construction techniques to create load-bearing components. Attention should be paid to the load direction relative to the layer orientation, as the different orientations often have different mechanical properties.

A smooth surface finish can also be an important property for architectural applications. SLA and MJM are methods with the smoothest surface finish, so no post-processing will be needed. For the other methods, post-processing is often required to achieve a smooth surface finish. In general, the thicker the layer, the more post-processing is needed.

Some methods are in a more advanced stage to be applied in the building construction than others. This is also shown in realized examples or plans for future projects. However, these projects are mostly demonstrations of using AM in constructing buildings. When these projects have proven to be successful and the cost of printing is reduced, more methods are expected to be commercialized and applied on a larger scale. In the coming years, existing and new AM methods and technologies are also expected to be developed, possibly expanding the application of AM in building construction.

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REFERENCES

- Apis Cor. 2017. “The First on-Site House Has Been Printed in Russia.” *Apis Cor*, February 20. <http://apis-cor.com/en/about/news/first-house>.
- ASTM International. 2010. “ASTM F2792-10: Standard Terminology for Additive Manufacturing Technologies.” West Conshohocken, PA: ASTM International. <https://doi.org/10.1520/F2792-12A>.
- Bos, Freek, Rob Wolfs, Zeeshan Ahmed, and Theo Salet. 2016. “Additive Manufacturing of Concrete in Construction: Potentials and Challenges of 3D Concrete Printing.” *Virtual and Physical Prototyping* 11 (3): 209–25. <https://doi.org/10.1080/17452759.2016.1209867>.
- Bourell, David L., Joseph J. Beaman Jr., Ming C. Leu, and David W. Rosen. 2009. “A Brief History of Additive Manufacturing and the 2009 Roadmap for Additive Manufacturing: Looking Back and Looking Ahead.” In *RapidTech 2009: US-Turkey Workshop on Rapid Technologies*, edited by Ismail Fidan and Fethi Calisir, 5–11. Istanbul: Rapidtech.
- Branch Technology. 2015. “Build like Nature with Cellular Fabrication.” <http://www.branch.technology/>.
- Breseghello, Luca. 2015. “A Performative Approach to 3D Printed Architecture.” Bachelor’s thesis, Polytechnic University of Milan. https://issuu.com/lucabreseghello/docs/lb_-_a_performative_approach_toward.
- Bruil BV. 2017. “Bruil Innovatie > 3D Printen.” <https://www.bruil.nl/doelgroepen/alles-voor-architecten/3dprinten>.
- Burgt, Adrie van der, and Bas van Wezel. 2014. “Large Scale Additive Manufacturing of Topological Optimized Beams.” Master’s thesis, Eindhoven University of Technology. <https://research.tue.nl/nl/studentTheses/large-scale-additive-manufacturing-of-topological-optimized-beams>.
- Caneparo, Luca. 2014. *Digital Fabrication in Architecture, Engineering and Construction*. Edited by Dipak Kumar Mandal and Chanan Singh Syan. Dordrecht: Springer.

- Carbon3D Inc. 2015. "Our Process." <http://carbon3d.com/clip-process>.
- Cesaretti, Giovanni, Enrico Dini, Xavier De Kestelier, Valentina Colla, and Laurent Pambaguian. 2014. "Building Components for an Outpost on the Lunar Soil by Means of a Novel 3D Printing Technology." *Acta Astronautica* 93: 430–50. <https://doi.org/10.1016/j.actaastro.2013.07.034>.
- Contour Crafting. 2017. "Contour Crafting: Robotic Construction System." <http://www.contourcrafting.org/>.
- Dolhan, Valentin. 2013. "3D Printing In Architecture: A Current State of the Industry, with Past and Future Perspective." Bachelor's thesis, VIA University College. https://www.academia.edu/10243998/3D_Printing_in_Architecture_-_A_current_state_of_the_industry_with_past_and_future_perspective.
- Feng, Peng, Xinmiao Meng, Jian-Fei Chen, and Lieping Ye. 2015. "Mechanical Properties of Structures 3D Printed with Cementitious Powders." *Construction and Building Materials* 93: 486–97. <https://doi.org/10.1016/j.conbuildmat.2015.05.132>.
- Frazier, William E. 2014. "Metal Additive Manufacturing: A Review." *Journal of Materials Engineering and Performance* 23 (6): 1917–28. <https://doi.org/10.1007/s11665-014-0958-z>.
- Gibson, Ian, David Rosen, and Stucker Brent. 2015. *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. 2nd ed. New York: Springer.
- Guo, Nannan, and Ming C. Leu. 2013. "Additive Manufacturing: Technology, Applications and Research Needs." *Frontiers of Mechanical Engineering* 8 (3): 215–43. <https://doi.org/10.1007/s11465-013-0248-8>.
- Hager, Izabela, Anna Golonka, and Roman Putanowicz. 2016. "3D Printing of Buildings and Building Components as the Future of Sustainable Construction?" *Procedia Engineering* 151: 292–99. <https://doi.org/10.1016/j.proeng.2016.07.357>.
- Hinojos, Alejandro, Jorge Mireles, Ashley Reichardt, Pedro Frigola, Peter Hosemann, Lawrence E. Murr, and Ryan B. Wicker. 2016. "Joining of Inconel 718 and 316 Stainless Steel Using Electron Beam Melting Additive Manufacturing Technology." *Materials & Design* 94: 17–27. <https://doi.org/10.1016/j.matdes.2016.01.041>.
- Keating, Steven J., Julian C. Leland, Levi Cai, and Neri Oxman. 2017. "Toward Site-Specific and Self-Sufficient Robotic Fabrication on Architectural Scales." *Science Robotics* 2 (5). <https://doi.org/10.1126/scirobotics.aam8986>.
- Keating, Steven J., and Neri Oxman. 2013. "Compound Fabrication: A Multi-Functional Robotic Platform for Digital Design and Fabrication." *Robotics and Computer-Integrated Manufacturing* 29 (6): 439–48. <https://doi.org/10.1016/j.rcim.2013.05.001>.
- Khoshnevis, Behrokh. 2004. "Automated Construction by Contour Crafting-Related Robotics and Information Technologies." *Automation in Construction* 13 (1): 5–19. <https://doi.org/10.1016/j.autcon.2003.08.012>.
- Labonnote, Nathalie, Anders Rønquist, Bendik Manum, and Petra Rüther. 2016. "Additive Construction: State-of-the-Art, Challenges and Opportunities." *Automation in Construction* 72: 347–66. <http://doi.org/10.1016/j.autcon.2016.08.026>.
- Le, Thanh T., Simon A. Austin, Sungwoo Lim, Richard A. Buswell, Alistair Gibb, and Tony Thorpe. 2012. "Mix Design and Fresh Properties for High-Performance Printing Concrete." *Materials and Structures* 45 (8): 1221–32. <https://doi.org/10.1617/s11527-012-9828-z>.
- Li, Yalun, Barbara S. Linke, Henning Voet, Björn Falk, Robert Schmitt, and Myron Lam. 2017. "Cost, Sustainability and Surface Roughness Quality: A Comprehensive Analysis of Products Made with Personal 3D Printers." *CIRP Journal of Manufacturing Science and Technology* 16: 1–11. <https://doi.org/10.1016/j.cirpj.2016.10.001>.

- Lim, Sungwoo, Richard A. Buswell, Thanh T. Le, Simon A. Austin, Alistair Gibb, and Tony Thorpe. 2012. "Developments in Construction-Scale Additive Manufacturing Processes." *Automation in Construction* 21: 262–68. <https://doi.org/10.1016/j.autcon.2011.06.010>.
- Materialise. 2016. "The Spider Bracket: A Topology Optimization Project by Altair, Materialise and Renishaw." <http://www.materialise.com/en/cases/spider-bracket-a-topology-optimization-project-by-altair-materialise-and-renishaw>.
- MX3D BV. 2017. "MX3D." <http://mx3d.com/>.
- Naboni, Roberto, and Ingrid Paoletti. 2015. *Advanced Customization in Architectural Design and Construction*. Cham: Springer.
- Oxman, Neri, Jorge Duro-Royo, Steven J. Keating, Ben Peters, and Elizabeth Tsai. 2014. "Towards Robotic Swarm Printing." *Architectural Design* 84 (3): 108–15. <https://doi.org/10.1002/ad.1764>.
- Pegna, Joseph. 1997. "Exploratory Investigation of Solid Freeform Construction." *Automation in Construction* 5 (5): 427–37. [https://doi.org/10.1016/S0926-5805\(96\)00166-5](https://doi.org/10.1016/S0926-5805(96)00166-5).
- Strauß, Holger. 2013. *AM Envelope: The Potential of Additive Manufacturing for Façade Construction. A+BE: Architecture and the Built Environment*. Delft: TU Delft.
- Suire, Anne-Christelle. 2016. "Une Imprimante 3D Pour Construire un Habitat D'urgence en 20 Minutes" [A 3D Printer to Construct an Emergency House in Just 20 Minutes]. Université de Nantes. http://www.iutnantes.univ-nantes.fr/1435591545031/0/fiche_actualite/.
- T. A. Grimm & Associates Inc. 2010. "3D Printer Benchmark: North American Edition." <http://www.tagrimm.com/benchmark-2010/>.
- Tay, Yi Wei Daniel, Biranchi Panda, Suvash Chandra Paul, Nisar Ahamed Noor Mohamed, Ming Jen Tan, and Kah Fai Leong. 2017. "3D Printing Trends in Building and Construction Industry: A Review." *Virtual and Physical Prototyping* 12 (3): 261–76. <http://doi.org/10.1080/17452759.2017.1326724>.
- TUM. 2017. "Custom Building Envelopes Straight from the Printer." <https://www.tum.de/en/about-tum/news/press-releases/detail/article/34151/>.
- US Bureau of Labor Statistics. 2015. "Census of Fatal Occupational Injuries." <https://www.bls.gov/news.release/cfoi.toc.htm>.
- Warton, James, Rajeev Dwivedi, and Radovan Kovacevic. 2014. "Additive Manufacturing of Metallic Alloys: An Architectural Case." In *Robotic Fabrication in Architecture, Art and Design 2014*, edited by Wes McGee and Monica Ponce de Leon, 147–61. Cham: Springer. https://doi.org/10.1007/978-3-319-04663-1_10.
- WATG. 2016. "The World's First Freeform 3d Printed House." <https://www.watg.com/the-worlds-first-freeform-3d-printed-house/>.
- Wolfs, Rob. 2015. "3D Printing of Concrete Structures." Master's thesis, Eindhoven University of Technology Department. <https://research.tue.nl/en/studentTheses/3d-printing-of-concrete-structures>.
- Wu, Peng, Jun Wang, and Xiangyu Wang. 2016. "A Critical Review of the Use of 3-D Printing in the Construction Industry." *Automation in Construction* 68: 21–31. <https://doi.org/10.1016/j.autcon.2016.04.005>.
- XJet Ltd. 2016. "Technology." <https://xjet3d.com/technology/>.
- Zeng, Kai, Deepankar Pal, Chong Teng, and Brent E. Stucker. 2015. "Evaluations of Effective Thermal Conductivity of Support Structures in Selective Laser Melting." *Additive Manufacturing* 6: 67–73. <https://doi.org/10.1016/j.addma.2015.03.004>.
- Zhang, Jing, and Behrokh Khoshnevis. 2013. "Optimal Machine Operation Planning for Construction by Contour Crafting." *Automation in Construction* 29: 50–67. <https://doi.org/10.1016/j.autcon.2012.08.006>.

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