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Review

Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0

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1. Introduction

The construction sector plays a key role in any country's economy. According to a report published by the World Economic Forum, the construction industry currently accounts for about 6% of the world GDP [1] and is expected to reach around 14.7% in 2030 [2]. Construction is a strategically important sector for the European economy involving a wide range of stakeholders and companies, providing 18 million jobs [209]. According to the World Economic Forum, a 1% rise in productivity worldwide could save $100 billion a year in construction costs [3], with the potential to contribute for a country's competitiveness and sustainable development [4–6].

The construction industry consumes a very significant proportion of the raw materials produced around the world, using for instance 50% of the global steel production, and is responsible for 30% of the world greenhouse gas emissions. Nonetheless, it provides the fabric of the built environment on which society depends [1,3]. The population living in urban areas is rapidly increasing, which impacts the need for affordable houses, public transportation and utility infrastructure.

Yet the perceived image of the construction sector is predominantly low-tech, still relying on craft-based methods, characterized by a poor performance and quality image [7–10].

The 2016 survey 'Sustainability in the Supply Chain' carried out by the Scape Group [11] concluded that 58% of all construction supplier and contractor respondents identified skilled workforce shortages as an obstacle for a future modernized construction sector.

Today, advanced technologies commonly used in the manufacturing sector are being exported for construction and architectural applications. Examples include incremental sheet forming and composite fabrication techniques (Fig. 1). However, contrary to other industries, construction has been slow to adopt new technologies and has never undergone a major disruptive transformation [14]. The uniqueness of the construction sector constitutes a challenge for the direct adaptation of technologies that are used in many other industries.

Other industrial sectors, such as automotive, aeronautics and aerospace underwent radical process changes by adopting digital technologies to improve quality and productivity. This digital transformation, usually described as Industry 4.0 [210–213], connects embedded system production technologies and smart production processes and is radically transforming industry and production value chains and business models. This industrial transformation is driven by a shift towards a physical-to-digital-to-physical connection enabled by the use of sensors and controls, augmented reality systems, cognitive and high-performance computing, additive manufacturing, advanced materials, autonomous robots and digital design and simulation systems, among other technologies. The construction sector is facing big challenges characterized by the adoption of digital technologies, sensor systems, intelligent machines, and smart materials. This transformation, which by analogy to the manufacturing sector has been called as Construction 4.0 (Fig. 2) [15–17], will enable construction companies to improve

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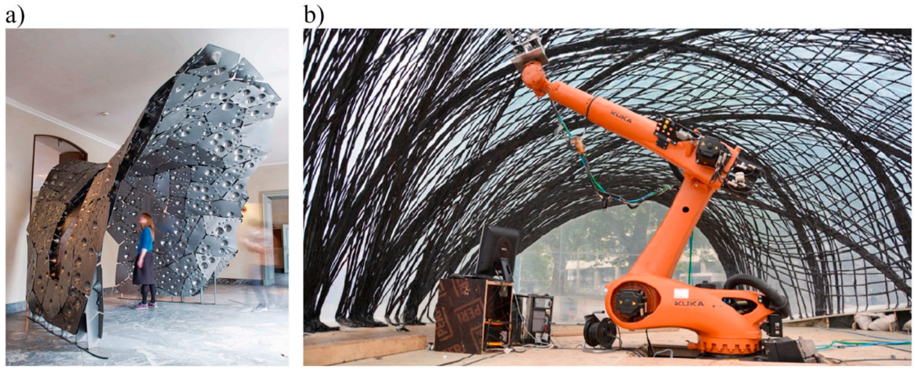


Fig. 1. a) The StressedSkins installation in exhibition at the Danish Design Museum. This is a single metallic organic structure produced by incremental sheet forming [12], b) Experimental fabrication set up of primary and secondary fiber bundles on pneumatic formwork [13].

productivity, reduce project delays and cost overruns, manage complexity, and enhance safety, quality and resource-efficiency [18,19]. According to a recent report from the Boston Consulting Group, within ten years full-scale digitalization in non-residential construction will lead to annual global cost savings of 13% to 21% in the engineering and construction phases and 10% to 17% in the operations phase [14]. According to a survey conducted by Roland Berger, 93% of construction stakeholders agree that digitization will affect each process but less than 6% of the construction companies are making full use of digital planning tools [16].

This paper discusses the digital transformation of the construction sector, in particular the potential of additive manufacturing for building construction as a key enabling technology of Construction 4.0.

The search was focused on the subject fields of architecture, engineering and construction (AEC), involving data collection from primary and secondary sources. To define the conceptual boundaries of our research, the most-searched keywords included concrete printing/ 3d printing in construction/AM in construction/digital construction/ industry 4.0/construction 4.0 and BIM. Articles containing a combination of these terms in the title/abstract/keywords were considered. This study was conducted through an extensive literature review using five online scholarly database sources (Springer, Scopus, Elsevier, Wiley and ISI Web of Science), as well books, technical reports and conference proceedings written in English language. Actual developments in AEC fields were also investigated by retrieving data from applied research published by relevant stakeholders and governmental reports. The authors subsequently scanned each article to filter and retrieve the most relevant ones.

The main additive manufacturing technologies being developed for construction are described, as well major challenges and opportunities. Detailed discussion of other technologies and concepts for Construction 4.0, included in the Fig. 2, such as logistics, sensors, IoT and cyber physical systems are outside the scope of this review.

2. Construction 4.0

Construction 4.0 will require the transformation of the construction industry towards the 4th industrial revolution, from automated production to a greater level of digitalization, through a BIM (Building Information Modelling) system connecting virtual and actual real building. BIM can be defined as a nD-based tool, designed to integrate the entire building information along the lifecycle of buildings, from design to construction, to operation and maintenance, and to reuse or demolition [20]. BIM, together with augmented reality, enhances decision making, allowing one to visualize how the design fits on-site before construction takes place, managing conflicts and checking structural safety problems during construction [21,22], as well supporting automated construction [23]. It can lead to optimized performance of buildings, by supporting building performance simulation and energy efficiency, using sensor technologies, such as thermography [24–27], as well as by promoting collaborative design development [28,29]. Advanced planning and building surveying are core tasks for constructions projects. 3D laser technology enables to digitally capture the dimensions and spatial relationships of objects, such as building structures, water pipes, etc., uploading this data into digital planning tools for teams working on BIM projects [30,31].

Integrating cloud computing technology with BIM allows project stakeholders to work in a real-time close collaborative way from different locations [32], based on the information permanently stored on the Cloud [33,34]. Cloud-BIM data can be accessed on by mobile devices, such as smartphones and tablet PC's [35,36], enabling timely access to updated information, this way improving decision-making and ensuring project delivery targets [37].

In addition to BIM, IoT (Internet of Things) is another technological development with the potential to transform the building industry. It is related to a system where objects are connected to the internet, via wireless/wired network connections and cloud cyber-infrastructure [38–40], through integrated or attached sensors [41]. Worksite safety can be significantly enhanced using IoT solutions. In the future, IoT technology will allow the connection of everything, from small accessories to large machines [42,43]. In the construction sector, IoT technologies and applications can transform the construction of new buildings, as well their maintenance and operation. IoT can maximize user comfort, security, and energy-saving by diverse intelligent solutions, such as optimizing user movement in a building, enhancing safety and security through smart control and detection, emergency planning, or smart energy and resource management [44,45]. Conversely, real-time information and diagnostic data is critical for predictive maintenance decision-making of mechanical assets, such as heating, ventilation, and air conditioning (HVAC) systems and elevators, as well for reducing maintenance costs.

The emergence of IoT technologies, Cloud Computing and BIM produce huge amounts of data that needs to be addressed, requiring Big Data technology [214,215], but they will also require sensitive information and processes to be protected through cybersecurity systems [46].

Nevertheless, the level of digitalization and automated production in the construction industry is still in an embryonic stage in comparison to other industries [47]. Eventually, the most dangerous and repetitive construction tasks can be performed in the future by robots [48,49], that will transfer data among each other and will ultimately have the ability to learn [50].

Additionally, unmanned aerial vehicles (UAV), also called drones, are increasingly used in the AEC fields and facilities management (FM) industry [51], having the ability to capture large amounts of data through multiple sensors, such as cameras, laser scanners, and Radio-frequency identification (RFID) readers [52–54]. UAVs are mainly used for tracking the progress of construction projects and making quality

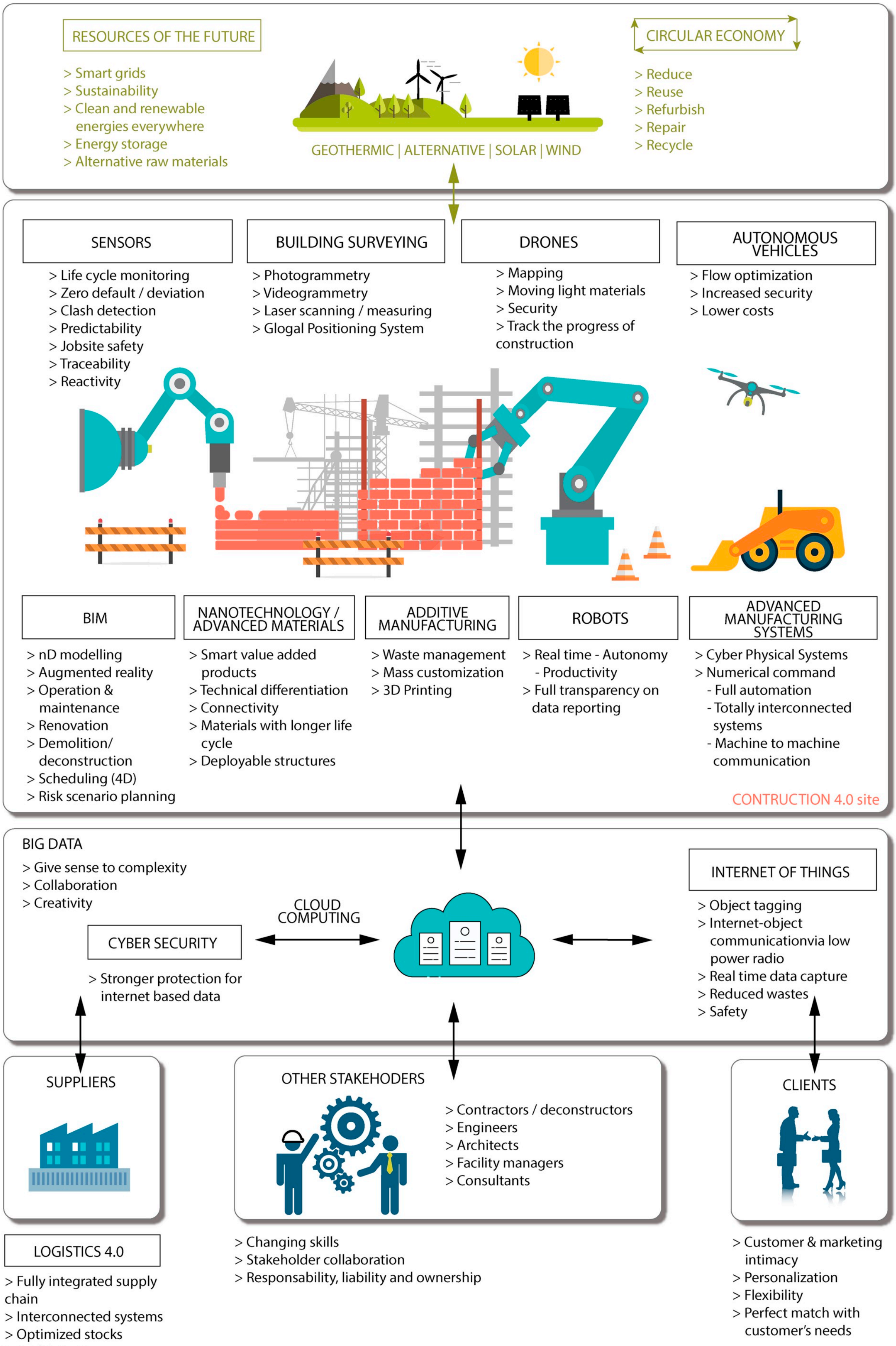


Fig. 2. The "Construction 4.0" environment enabled by intensive use of digital technologies.

assessments, apart from monitoring building sites and realizing dangerous tasks, this way increasing workplace safety [15,55–57]. The use of drones is also being used for masonry assembly [58,59] or aerial additive building manufacturing [60].

The transformation of the construction industry into a digital and innovation-based sector will drive construction towards the application of automated modelling and manufacturing processes [61–63]. Additionally, this new construction digital environment will promote collaboration among the stakeholders, creativity, strengthening the supply chain, promoting on-demand supply.

3. Additive manufacturing in construction

Additive Manufacturing (AM) is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM [American Society for Testing and Materials] Standard). AM, was initially used to produce conceptual product models for aesthetics and ergonomic purposes, identifying design flaws and testing products during the design process (Fig. 3). Today, actual product manufacturing is increasing, and toys, furniture, automotive and aerospace products and medical devices are among the many items being produced with this technology [68,69]. The increasing industrial use of AM processes is due to their unique characteristics [70–73], namely:

- No need for tooling, which significantly reduces production time and costs;
- Possibility to quickly change designs;
- Product optimization for function;
- More economical custom product manufacturing (mass customization and mass personalization);
- Potential for simpler supply chain, shorter lead times and lower inventories.

Fig. 4 shows the typical information flow of an AM process. A computer model is first generated using a CAD system (solid or surface model), being tessellated and converted into the standard STL format, which is then sliced in multiple cross-sections that are sent to the AM system [72,74–77]. The CAD model must be a 3D solid, using either Constructive-Solid-Geometry (CSG) or Boundary-Representation (B-rep). The STL file format is conceptually simple and easy to generate but presents problems related to its size and numerical accuracy [78]. It is also not possible to specify material properties, so the fabrication of multi-material structures requires the use of multiple STL files (Fig. 5), which is an important drawback as AM has high potential to produce heterogeneous structures with varying materials or densities (functionally graded structures). The representation of these materials requires both geometric modelling and material modelling [79,80]. Geometric modelling of heterogeneous objects includes manifold solids, r-sets, s-sets, non-manifold solids, selective geometric complex (CGC), constructive non-regularized geometry (CNRG) and discrete representations like voxel-based modelling and implicit functional representation (F-Rep) [79–84].

Alternatives to STL include directly slicing CAD, IGES and STEP formats. Recently, a file format called Additive Manufacturing File (AMF) was developed by ASTM using curved triangles based on second degree Hermite curves (other element geometry is also possible), including the possibility to add material properties [78]. Contrary to the STL file, which is the standard file format for AM there is no industrial standard for slicing data. Few general methods have been proposed including the Common Layer Interface (CLI), Layer Exchange ASCII Format (LEAF) and SliCe format (SLC) [85–87]. The slice format generates the NC (Numerical Control) information to control de AM system. The fabrication process can be controlled based on vectors (movements in straight lines; curves approximated to segments) or raster (individual dots, like a monotone bitmap). Table 1 summarizes the main AM manufacturing technologies that have been used for construction applications.

Due to the specific nature of each technology and the type of materials and size of building elements, the AM processes used in the construction sector are mainly extrusion-based and binder jetting

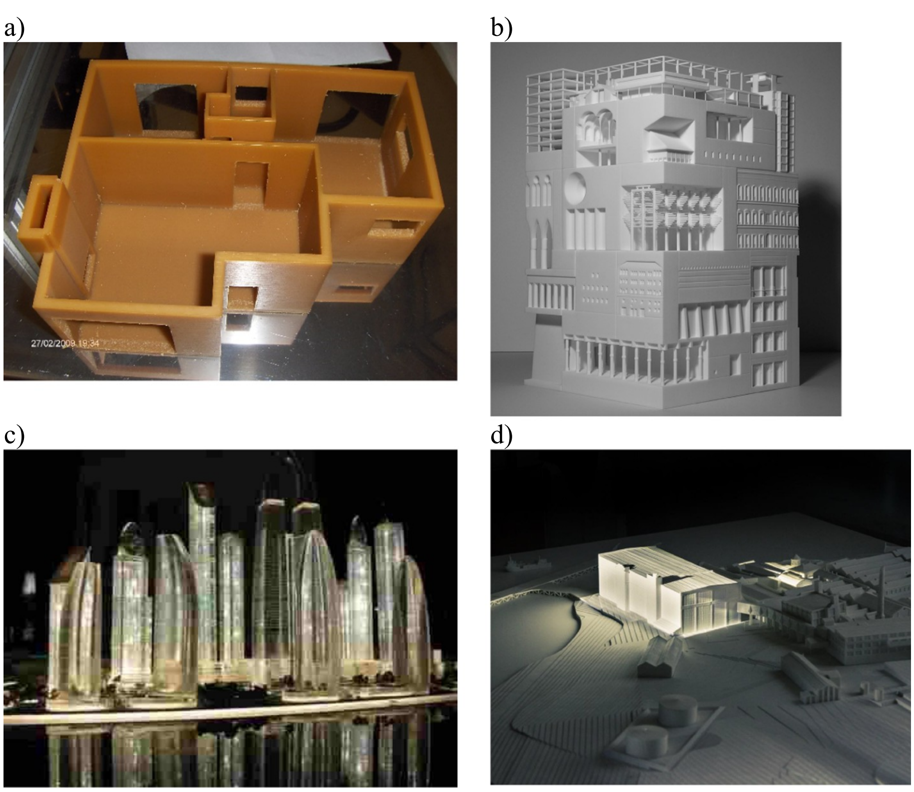


Fig. 3. Examples of AM made building models: a) Dwelling house model produced with ThermoJet (3D Systems) [64], b) Single model containing pieces of 35 different famous buildings (from the 18th century BCE to 2005) created by Fumio Matsumoto [65], c) SLA Clear Resin Buildings [66], d) Projection on a 3D Printed Model [67].

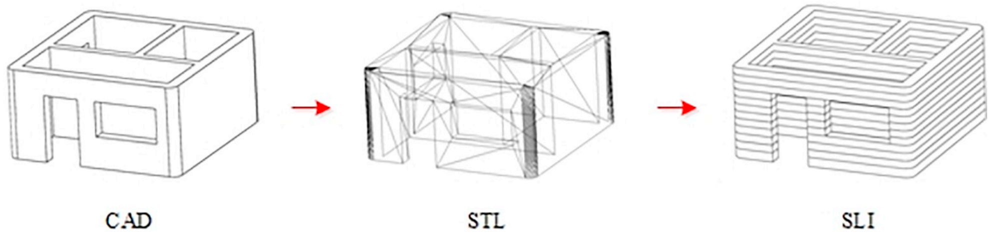


Fig. 4. Main steps to produce a physical object through AM.

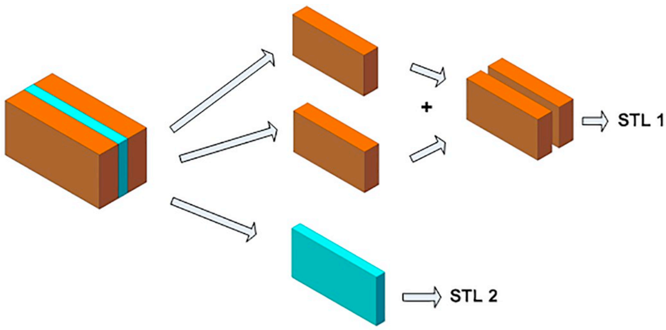
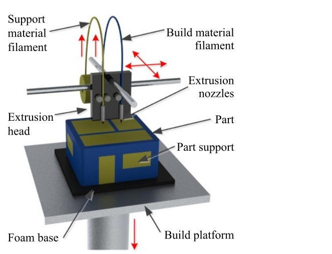
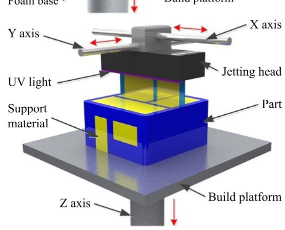
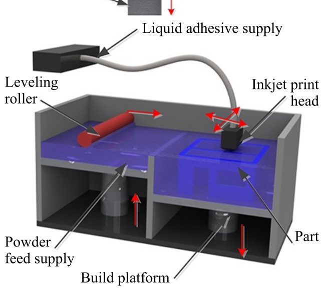
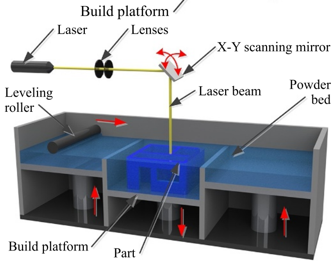


Fig. 5. Multiple STL files for multi-material components.

Table 1
AM technologies used for construction applications.

	**Material extrusion** – an additive manufacturing process in which material is selectively dispensed through a nozzle
	**Material jetting** – an additive manufacturing process in which droplets of build material are selectively deposited
	**Binder jetting** – an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials
	**Powder bed fusion** – an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed

processes for off-site and on-site applications, including the fabrication of new construction elements/houses or repairing applications (Fig. 6).

3.1. Extrusion-based processes

Extrusion-based processes can use print-heads mounted in frames, robots or cranes.

3.1.1. Cement/ceramic paste materials

The Contour Crafting process, one of the first AM technique proposed for the construction industry, was developed by Khoshnevis [92]. This is a multi-material deposition technology combining an extrusion process to form the object surfaces (outer regions of the structure) and a filling process (by pouring, casting or extrusion) to build the core region of the structure [92,93]. The Contour Crafting process has been used to extrude concrete or ceramic paste materials through a 3D printing-head mounted on an overhead crane [93]. The process requires support structures to create overhangs and the surface roughness of printed structures is smoothed out using a trowel. For the fabrication of a door or window, a lintel is placed to bridge the gap between walls, and the upper part of the wall is printed on top of the lintel. It is limited to vertical extrusion, allowing co-extrusion of multiple materials [94]. The Contour Crafting technique has been validated through the construction of small scale structures and housing scale walls [95], and successfully produced wall elements of 2 m high with a width of 13.5 cm at a speed of approximately 1 square meter per hour [94,96–98].

Bosscher et al. [99] proposed a mobile contour crafting platform driven by a translational cable-suspended robot. The system called Cable-Suspended Contour-Crafting (C^4) Robot includes an extrusion system for laying beads of concrete as well computer-controlled trowels for forming the beads as they are laid. The system uses cable robots, which are relatively inexpensive, easy to transport, as well disassemble and reassemble. It was developed to build large structures, reducing costs and increase the portability.

There are other techniques similar to Contour Crafting, for commercial or academic applications, developed by different companies or research groups, such as WinSun (China), TotalKustom (USA) [100], BetAbram (Slovakia) [101], CONPrint3D (Germany) [102], HuaShang Tengda (China) [103], China State Construction Engineering Corporation [104], Specavia (Russia) [105] and ICON (USA) [106].

WinSun, a pioneer company in this field that successfully printed a group of 200 m^2 houses in 2014, uses a large system (150 × 10 × 6.6 m) to print large scale building components, assembling them at the construction site (Fig. 7). The printing material contains glass fiber, steel, high-grade cement, hardening agents and recycled construction waste materials [88,107].

The Concrete Printing technology (Fig. 8a) is a gantry-based system developed at the University of Loughborough, UK [8,110]. Several conventional construction materials have been used, including gypsum (used as support material) and commercial pre-packaged mortars (used as build material), optimizing the operating parameters (flow rate, nozzle, shape and size and rheological properties) [8,108,109,111]. Prepared mixtures are placed in a hopper on the top of the print-head, and then extruded as a predefined filament shape. Diverse nozzle

Fig. 6. AM processes used in the construction sector: a) 3D printed office in Dubai [88], b) Apis Cor 3D printed house [89] c) Pedestrian bridge produced by D-Shape technology [90], d) The Europe Building (The Netherlands) [91].

diameters, ranging from 4 to 9 mm, have been used [98,108,109]. The print head moves back to the recharging position to refill whenever the amount of material in the hopper reaches a critical value [98,111,112]. A curved bench (2 × 0.9 × 0.8 m) (Fig. 8b) was produced as a proof of concept, using 128 layers printed at a speed of 20 min/layer [113]. Contrary to the Contour Crafting technique, this process does not use trowels, thus creating structures with rough surface finishing.

Gosselin et al. [112] developed a system based on an extrusion print head mounted on a 6-axis robotic arm (Fig. 9). This system includes 2 peristaltic pumps, one for the premix and another for the accelerating agent and a premix mixer. The fabrication process includes two main steps. Firstly, a mortar premix with an appropriate rheological behavior is prepared and kept in a shearing mixer. Then, the premix is pumped to a screw-assisted print head using a peristaltic pump. Additives are simultaneously dispersed in the mix to accelerate the setting of mechanical properties after extrusion [112]. Fig. 10a shows an example of a 3D printed concrete multifunctional wall produced by Gosselin and co-workers [112,115]. CyBe Additive Industries (The Netherlands), developed a comparable system containing a print-head attached to regular robot-arms to extrude a proprietary mortar printed at a maximum speed of 600 mm/s and layer thicknesses up to 50 mm [114] (Fig. 10b).

Cybe and Arup [116,117] recently printed a 100 square meter concrete house made by 35 modules fully printed in 48 h (Fig. 11b). CON3D, a Spanish consortium, also developed a robotic extruder equipment to produce layered concrete structures [120], while Bruil (The Netherlands) uses a robotic arm to produce high-quality façade elements with gradients of color [121]. Likewise, Sika developed a mortar mixed with a range of additives allowing the cure in seconds, while ensuring a correct bonding with the previous layer. This material is extruded by a printing head connected to a robot moving at high speed [118] (Fig. 11a).

3D Printhuset developed 4 gantry type 3D printers with different sizes, the larger one allowing a printing volume of 9.5 × 19.5 × 5.8 m, extruding layers with 20 mm (height) × 50 mm (width) at 8 m/min. The cement based concrete material incorporates recycled tiles and sand as aggregate [119] (Fig. 11c). Zhang et al. [122] also uses a gantry printer to extrude nano-clay concrete specimens.

Apis cor uses a mobile crane printer rotating 360°, which can print within 3.1 m around with a speed of 10 m/min and a precision of ± 0.5 mm. Both concrete and geopolymer can be used as construction materials [89].

Perrot et al. [123] successfully 3D printed earth-based materials with a 6-axis robot, using alginate to increase the green strength. Conversely, the World's Advanced Saving Project (WASP) has been developing large size delta printers to extrude construction materials [124]. A 12 m-tall 3D printer was also used to print walls made of clay reinforced with straw fibers, reaching 3 m [125]. A smaller, 4 m tall WASP 3D printer was used by Asprone et al. [126] to make reinforced concrete elements to be assembled together by a steel reinforced system (Fig. 12a).

In 2016, TU Eindhoven built a gantry robot with 4 DOF (degree-of-

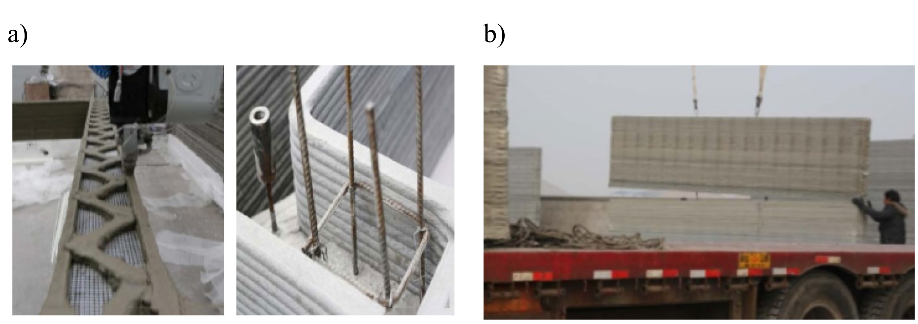


Fig. 7. a) Printing process, b) Transport and assembly of printed components [88].

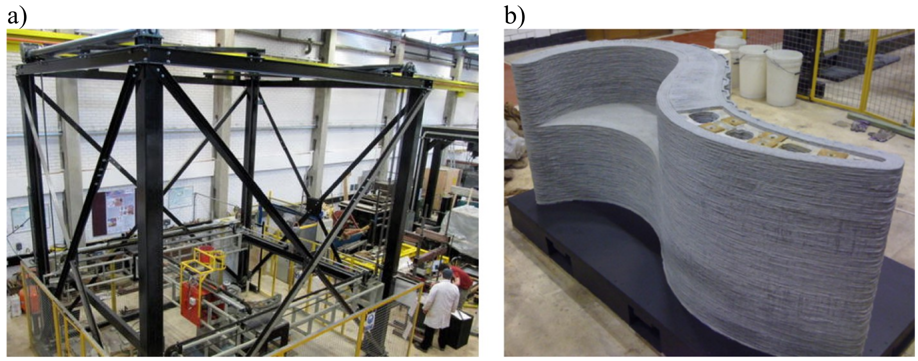


Fig. 8. a) The printing frame of Concrete Printing [108], b) The printed Wonder Bench [98].

freedom) able to print within a volume of 9 × 4.5 × 2.8 m. A mixer-pump uses a pressure of 1-3 MPa to deliver a cement-based concrete to the nozzle, with a printing speed of 100 mm/s [127].

Recently, this group produced a bridge with a span of 6.5 m and a width of 3.5 m, composed of 6 printed elements pressed together by post-tensioned prestressing tendons (Fig. 12b). A specific nozzle was developed to deliver a reinforcement cable together with the extruded concrete [128]. Similarly, Lim et al. [129] and Ma et al. [130] used steel cable extruder systems to improve flexural strength of geopolymer composites [129].

The Institute for Advanced Architecture of Catalonia (IAAC) developed the concept of "minibuilders" (Fig. 13a), using a family of three small robots capable of printing concrete [131,132]. In this case, one or more foundation robots create the footprint of the structure, followed by grip robots clamped onto the footprint to produce the structure, using as support the previously printed layers. The grip robots are capable of printing ceilings and lintels horizontally. Finally, a vacuum robot moves over the printed structure, reinforcing it by applying additional layers [131]. The system is very flexible though not able to print complex shapes and high layer thickness structures [133]. In 2018, Zhang et al. developed multiple mobile robotic arms to print together a concrete structure, monitored by a stereo camera to avoid collisions [134].

Craveiro et al. [64,135–138], explored the concept of screw-assisted/pressure-assisted printing heads to create concrete, clay and multi-material structures. Firstly, a system called RapidConstruction was developed, comprising a building platform, a linear movement system and two extrusion heads, each with a screw system allowing the processing of different materials. The controller can control 4 axes (3 axes with x-y-z linear movement and the rotation of the extrusion head), monitoring its movement through each encoder. The first extrusion head was able to produce contour paths, smoothing the material on the lateral surfaces, through parallel guiding blades. The second extrusion head, used to create composite meshes, had neither rotational freedom nor lateral guides. This system was later optimized to print multi-material/functionally graded structures [64], and a computational tool was developed to design and fabricate these structures [139,140]. Recently, Craveiro et al. [141] produced functionally graded concrete-cork element structures using a robot coupled with a multi-material printing head.

ETH Zurich patented a fabrication process called Smart Dynamic Casting, where a small formwork (compared to the produced structure) is attached to a 6-axis robotic arm programmed to move vertically (Fig. 13b). The concrete material slowly flows from the bottom of the formwork, this way forming a column. To ensure an optimal formability of the concrete, a feedback system is constantly evaluating the properties of the material, adjusting the velocity of the movements [113,142].

3.1.2. Polymer-based materials

Extrusion-based systems were also used by the Dutch company DUS Architects and partners in Amsterdam, to print large polymeric components up to 2 × 2 × 3.5 m, for a project named 3D Print Canal House [133]. The components were produced off-site and assembled on-site. To celebrate the Dutch presidency of the European Union in 2016, DUS Architects developed fully recycled façade elements for the "Europe Building" as illustrated in Fig. 6d. Large scale thermoplastic polymer extrusion is also being explored by Branch Technology (USA), which developed an algorithm to create cell-like matrix geometries in open spaces (Fig. 14a) without the use of support materials [143]. ETH Zurich patented a method to robotically fabricate polymer-based 3D meshes combining formwork and reinforcement [147–149]. Recently,

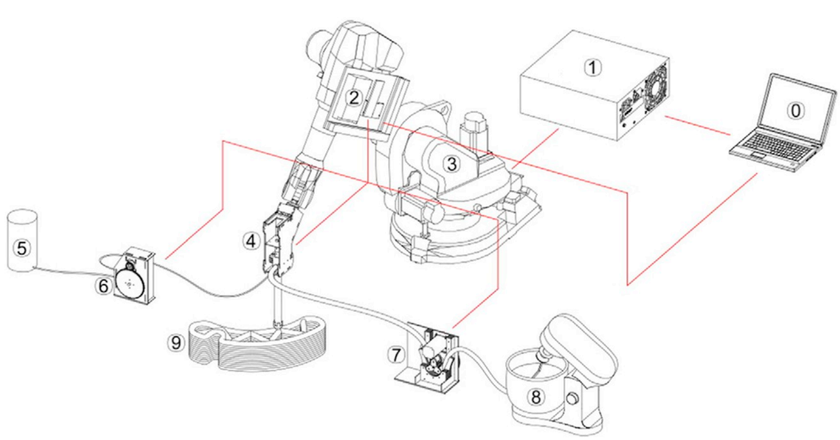


Fig. 9. Schematic of the 3D printing setup: 0. System command; 1. Robot controller; 2. Printing controller; 3. Robotic arm; 4. Printhead; 5. Accelerating agent; 6. Peristaltic pump for accelerating agent; 7. Peristaltic pump for premix; 8. Premixer; 9. 3D printed object [112].

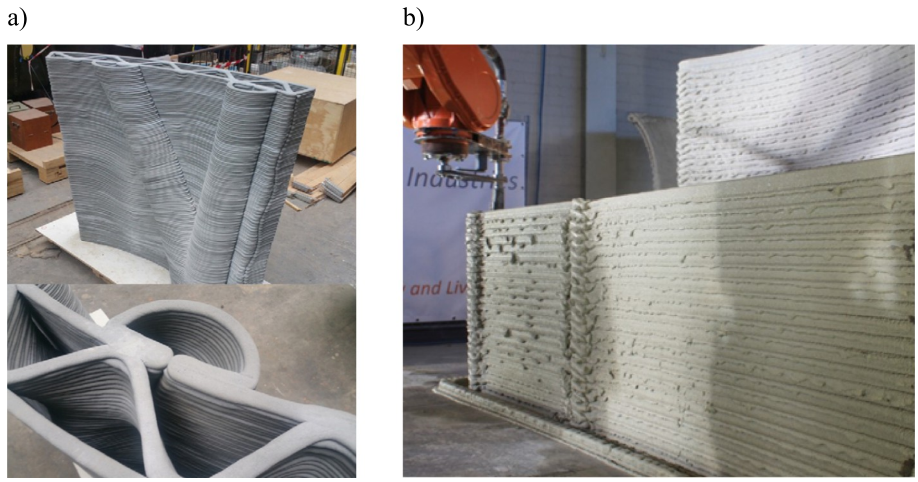


Fig. 10. Examples of 3D printed concrete walls. a) Concrete wall by Gosselin [112], b) Concrete wall by CyBe [114].

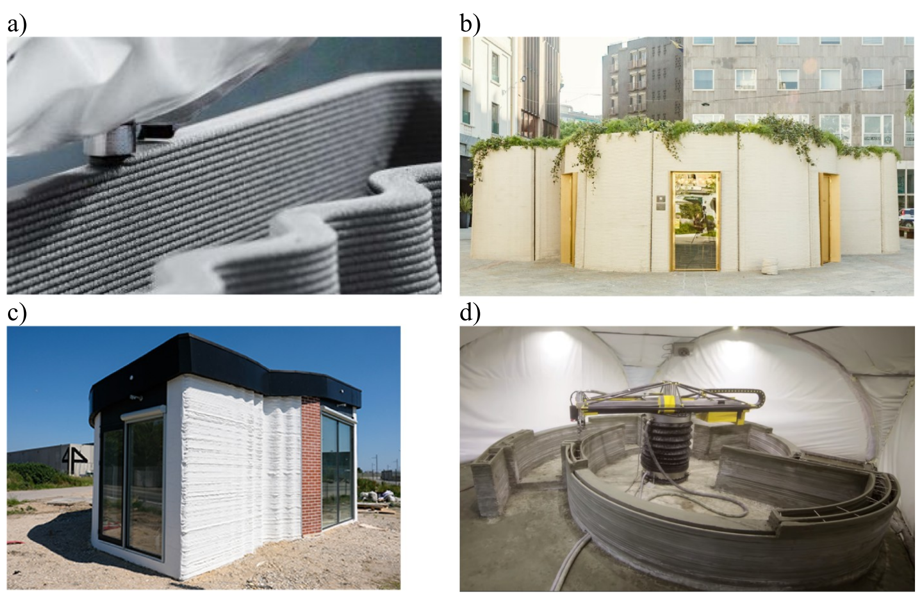


Fig. 11. a) Sika's 3D concrete printing technology [118], b) ARUP 3D Housing 05 (Milan) [117], c) 3D Printhuset printing [119], d) Apis Cor crane printer [89].

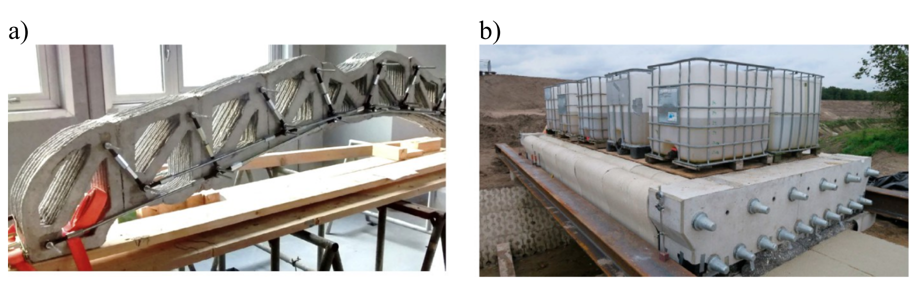


Fig. 12. a) 3D printed beam with a steel reinforcement [126], b) In-situ testing of the printed bridge [128].

the team focused on the development of an automated bending and welding process to create steel rebar reinforcement meshes [150].

In 2013, Skanska (SE) was a pioneer in using 3D printed parts for the 6 Bevis Marks office project in London [144]. The junctions between the roof's supporting steel structure and the columns received ethylene tetrafluoroethylene (ETFE) claddings pieces produced by AM (Fig. 14b).

The Oak Ridge National Laboratory (USA) developed an AM system called Big Area Additive Manufacturing (BAAM) capable of producing large scale polymer elements. This technology was demonstrated by the project Additive Manufacturing and Integrated Energy (AMIE) (Fig. 14c), which includes a vehicle and a building structure composed by 11 3D-printed C-shaped sections made by carbon fiber-reinforced ABS composite, covering an area of 19.5 m^2 [145,151].

In 2017, 3D printed polyurethane (PU) foams were used to produce architectural scale prototypes, either by MIT [152] or the University of Nantes (project YHNOVA Batiprint3D) [153]. This two research groups used two-component fast-curing PU foams sprayed by a printing head

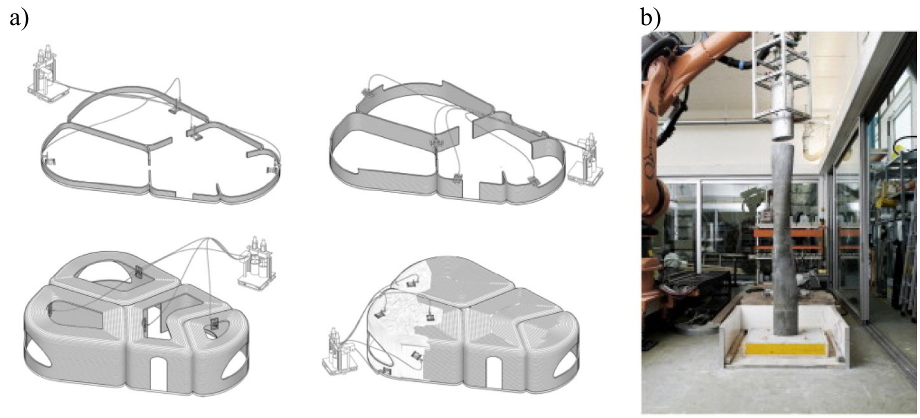


Fig. 13. a) The minibuilders fabrication process [131], b) Smart dynamic casting [113].

Fig. 14. a) The Shop Pavillion [143], b) ETFE claddings [144], c) AMIE building [145], d) 3D printed glass columns [146].

connected to a robotic arm to create freeform hollow walls. These foam structures can be used as insulation material or formwork, after being filled with concrete.

3.1.3. *Novel materials for Earth applications and beyond*

Khoshnevis et al. [154] presented an extrusion system using sulfur concrete, a construction material with possible use in Earth's construction and potential advantages for planetary construction, such as on Mars, where it is abundant and safe to use due to the range of temperatures in the planet.

Geopolymers are also been explored for terrestrial and extra-terrestrial use. The Pennsylvania State University developed a metakaolin-based geopolymer concrete for the NASA's 3D-Printed Habitat Challenge. A printed dome structure was submitted to a compression test, after 18 h of curing, and failed at 7.9kN [155]. For the same competition, Singapore Centre for 3D Printing, developed fly ash based geopolymers for 3D concrete printing [156].

3.1.4. *In-situ retrofit/repair technologies*

Most of 3D printing technologies developed for the construction industry are used to build new buildings/parts, though buildings and civil infrastructures need to be maintained, repaired and retrofitted [157]. Reverse engineering technologies as laser scanner [31], infrared thermography [24] and photogrammetry [158] have been used to develop in-situ printing models adapted to existing constructions. Moreover, robotic vertical extrusion techniques and tailored materials, such as foam concrete [159] or cementitious materials incorporating fly ash cenosphere [160] (Fig. 15), are being used to apply layers upon existing walls.

3.2. *Jetting processes*

The first attempt to use a binder jetting technology in construction was made by Pegna [161], based on the deposition of a layer of reactive material (Portland cement) over a layer of sand. Final consolidation was performed by applying steam in a pressurized steam chamber (3 atm and 300 °C) [161].

The D-Shape technology was developed to build medium size structures, using sand and a binder to create stone-like structures. In this process, a horizontal 5–10 mm layer of sand material is deposited

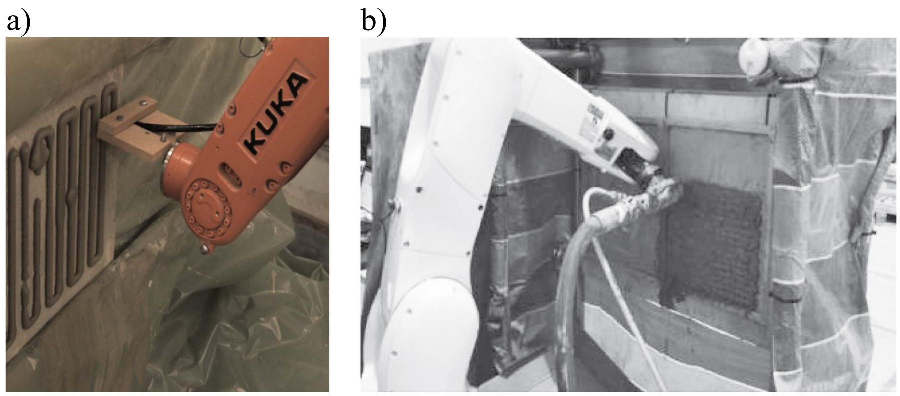


Fig. 15. Vertical 3D Printing with robots, using: a) foam concrete [159], b) cementitious material incorporating fly ash cenosphere [160].

over the entire building area, using a printing head attached to a gantry [162,163]. Spraying heads (300 array injection nozzles, 6 × 6 m unit), shown in Fig. 16a, move horizontally and a predefined amount of liquid binder is sprayed to selectively bind the powder material at 1.0 mm resolution [164]. The binders, initially based on epoxy or polyurethane materials were gradually replaced by more eco-friendly organic binders [133].

After the printing process, the remaining sand must be removed, and the building surface treated. The non-processed sand, which acts as support material during the fabrication process, can be reused.

Emerging Objects (USA) developed a rapid concrete masonry unit that uses inkjet sprays to bind fiber-reinforced cement mixture with small-sized aggregates (Fig. 16b) [165,166]. Shakor et al. [167] produced specimens made of calcium aluminate cement and Portland cement, selectively dropping water with a Z-corp 150 equipment. CONCR3DE (The Netherlands) uses inkjet technology to produce inorganic polymer material architectural elements [168]. Similarly, Xia and Sanjayan [169] used a binder jetting technology to print geopolymer specimens for construction applications.

Complex molds, to be filled with concrete, were also produced by AM technologies for the construction sector, and these molds can be later removed or not. Dillenburger et al. [170] printed non-removable sandstone molds to produce prefabricated large-scale building components with highly detailed and complex geometry. Conversely, 3Dealise and Bruil companies used a giant 3D printer to produce sand-based molds for concrete (1.800 × 1.0 × 0.7 m), easily removable with pressured water after the concrete set [171]. Gardiner et al. [172] developed a process called FreeFAB Wax for producing wax molds for concrete, requiring different steps: i) wax printing, ii) surface mill, iii) concrete pour, iv) wax melt off and recycling.

Another binder jetting technology was used by Weger et al. [173] and Pierre et al. [174] to investigate the penetration of cement pastes into aggregates. The components are produced layer by layer selectively applying cement paste on an aggregate packing through a nozzle.

3.3. Fusion of high melting point materials

Metallic structural elements for construction can also be produced by AM techniques, which offer the possibility to build customized freeform architecture with reduced weight. Arup used a powder bed fusion technology to create tailored structural nodes to connect cables to struts for a shopping street in The Hague [175]. Power bed fusion was also used to produce optimized complex façade nodes using aluminum powders [176].

TU Dresden has a project on 3D-printing of steel reinforcement bars, using a gas-metal arc welding equipment together with a 3-axis CNC system. This group tested the tensile properties of the steel bars, as well the bond between these bars and a 3D printed concrete developed by them [177]. Result show a reasonable bonding between the steel bars and the concrete element. MX3D from the Netherlands printed a fully functional steel bridge using a similar welding machine coupled to a robot [178] (Fig. 17a). This technology, investigated for the construction sector and for other industries [181], uses stainless steel wire as printing material, which is 10 times less expensive compared to the SLM powders used in the metal sintering equipment.

Fusion technologies were also used to produce glass objects using both natural energy from the sun and sand (raw material). In this case, a mechanical equipment moves a sand box along 3-axis and uses a large Fresnel lens (1.4 × 1.0 m) to focus the sun, producing this way temperatures between 1400 °C and 1600 °C, which melt the sand and build parts layer by layer [179] (Fig. 17b). Similarly, Lou et al. [182] used SLM technologies through a CO_2 laser to locally melt soda lime glass, creating transparent glass structures. On the other hand, MIT explored a melting followed by printing technology to make architectural size

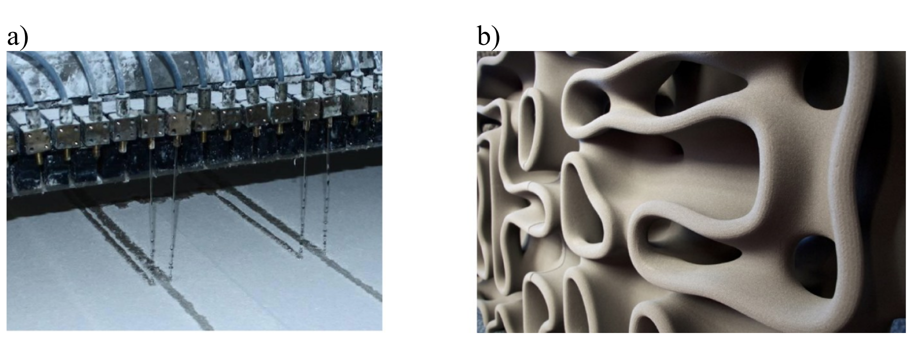


Fig. 16. a) Detail of the printing process, where the binder is sprayed on the sand [164], b) Printed sand structure by Emerging Objects [165].

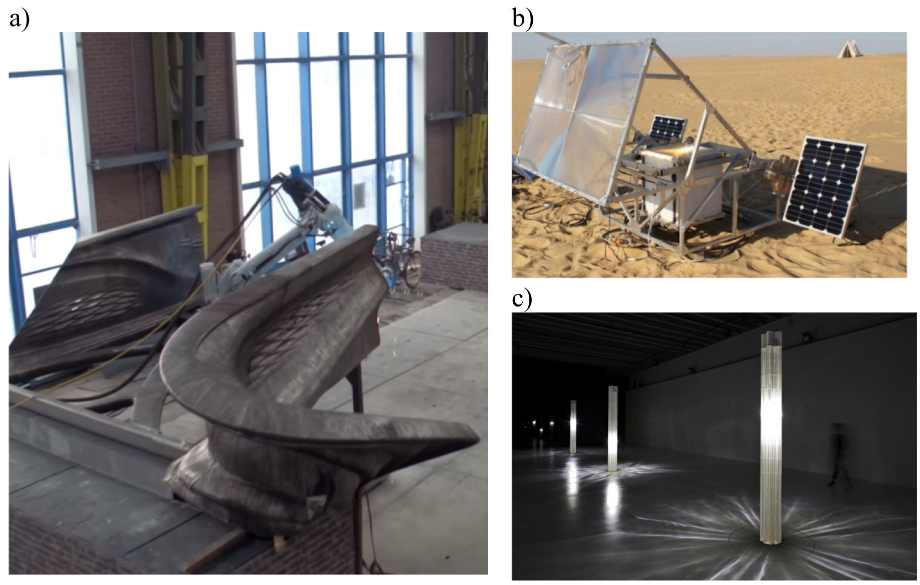


Fig. 17. a) Fully functional steel bridge in construction [178], b) Sintering sand [179], c) 3D printed glass columns [180].

glass building components with tunable and predictable mechanical and optical properties. This technology, called G3DP2 (glass 3D printing project), was used to print 3 m-tall glass columns [180] (Fig. 14d).

Table 2 provides a summary of AM technologies for both in-situ or off-site construction according to the printer type and technology.

4. Materials

Using AM as a platform for materials design allows the use of natural and recycled materials contributing to a more sustainable construction approach, which is one of the targets of Construction 4.0. As reported in the previous section, most research groups are exploring AM for concrete-printing, though for a functional extrusion of concrete it is important to improve its fresh properties, such as extrudability, buildability and pumpability, as well to control the deviation from the design nozzle height during printing process [183,208].

The size of the aggregate must be compatible with the opening diameter of the nozzle to avoid its blocking [184]. Workability needs to be preserved over time, and the support of subsequent layers must be

Table 2
Summary of AM technologies for construction[a].

Printer type	Technology			
	Extrusion-based		Jetting	Fusion of high melting point materials
	In-situ	Off-site	Off-site	Off-site
Robot/crane printer	- Aachen University (CF) [159] - Apis Cor (CE) [89] - Batiprint3D (PF) [153] - Branch Technology (P) [143] - ETH Zurich (CE) [113] - ETH Zurich (P) [148] - MIT (F) - [152] - SC3DP (CE, GE) [134,156,160] - Spectavia (CE) [105]	- Bruil (S) [121] - CON3D (CE) [120] - Cybe (CE) [114] - Sika (CE) [118] - The Pennsylvania State University (CE, GP) [141,155] - Xtreee (CE) [115]		- FreeFAB Wax (P) (J.B. [172]) - MX3D (M) [178]
Gantry printer	- BetAbram (CE) [101] - HuaShang Tengda (CE) [103] - TotalKustom (CE) [100]	- 3D Print Canal House (P) [91] - 3D Printhuset (CE) [119] - BAAM (P) [151] - Concrete Printing (CE) [110] - Contour Crafting (CE) [92] - G3DP2 (G) [180] - RapidConstruction (CE, CL, P) [136] - Southeast University China (CE) [122] - TU Eindhoven (CE) [127] - Winsun (CE) [88]	- 3Dealise (S) [171] - CONCR3DE (S) [168] - D-Shape (S) [162] - Emerging Objects (P) [165] - ETH Zurich (S) [170] - Pegna (CE) [161] - Pierre et al. (CE) [174] - Swinburne University of Technology (G) [169] - TUM (CE) [173] - University of Technology Sydney (CE) [167]	- Arup (M) [175] - MST (G) [182] - Nematox (M) [176] - Skanska (P) [144] - Solar Sinter (G) [179]
Other systems	- Minibuilders (CE) [132]	- C^4 Robot (CE) [99] - WASP Delta Printers (CE, CL) [124]		- TU Dresden (CE) [177]

[a] CE: cement-based; CF: cement foam; CL: clay-based; G: glass; GP: geopolymers; M: metal; P: polymer-based; PF: polymer foam; (S): sand-based.

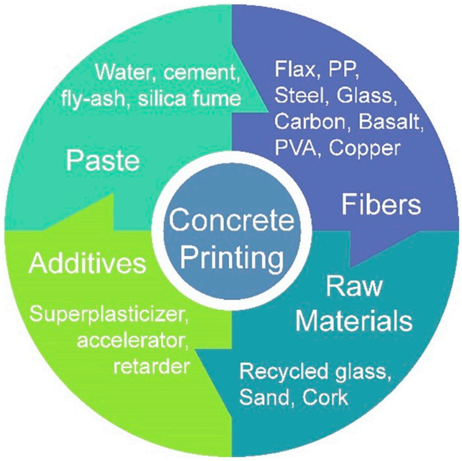


Fig. 18. Materials used for concrete-printing.

ensured through early setting of concrete [108,109,185], keeping the bond strength between filaments [186]. The properties of the concrete can be enhanced by an optimal proportion of each mixture ingredients, namely by adjusting the water/binder (cement, fly-ash, silica fume) ratio and controlling the quantities and size of raw materials, such as river sand [187], recycled glass [188] or cork [141], as well using additives (superplasticizer, retarder and accelerator). The fibers also play an important role in the stability of the compounds. Different fiber types are commonly used in AM for construction, from natural to highly technological ones, i.e. flax fibers [189], copper fibers [190], carbon fibers [155], glass fibers [191], basalt fibers [192], steel fibers [7], polypropylene fibers (PP) [193] and polyvinyl alcohol (PVA) [194]. Fig. 18 shows materials used for concrete-printing.

5. Lightweight and functionally graded structures

The European Commission approved a flagship initiative called "Resource efficient Europe" [195]. Resource efficiency, based on a circular economy strategy, considers an efficient use of energy, natural resources, and materials. It is fundamental to actively seeking the reduction of CO_2 emissions and encouraging energy savings [196,197].

A resource efficient construction sector with lightweight structural components will help to reduce waste generation, emissions and global resource consumption [138,198,199]. On the other hand, thin/lightweight walls avoid overloading the building structure, reducing cement consumption [139,200], which is responsible for the production of approximately 5–8% of CO_2 worldwide [201].

To minimize the weight of concrete structures, Keating and Oxman [202] from the MIT Mediated Matter group developed a strategy to print concrete with varying density, by mixing concrete with aluminum powder and lime, which react to produce hydrogen gas bubbles responsible for creating a foaming structure. Similarly, Chee et al. [203] used a robot together with a controlled syringe dispenser to inject aluminum solution in specific locations of a white cement panel, creating personalized patterns of holes. Herrmann and Sobek [204] also used graded spraying techniques to produce mass-optimized structural components.

Another way to reduce weight is to create topological optimized construction structures.

The Institute for Advanced Architecture of Catalonia (IAAC) improved the shape of the first pedestrian bridge produced by AM (D-Shape technology) through topological optimization, minimizing the amount of waste and maximizing structural performance by an optimized material distribution [90].

Dillenburger et al. [170] proposed a method to fabricate slabs with both topology and shape optimization. This group used powder-bed technologies to make a polymer-sand composite mold, filled with ultra-high-performance reinforced concrete (Fig. 19a). Likewise, Rippmann et al. [205] reduced up to 70% the weight of 3D sand-printed floor prototypes by varying rib geometries.

Craveiro et al. [139] presented a parametric system to model, simulate and fabricate construction elements (building walls) with varied porosity, changing the internal pore size according to internal stresses. In 2017, Craveiro et al. [206] used different computational tools to generate lightweight building walls for 3D printing, one based on topology optimization, resulting in an enhanced shape design, and another based on material/porosity optimization to make a material graded design.

Metal structures can also be optimized using AM technologies. An Arup's research project reduced up to 40% of the total structure weight by topological optimization of metal structural nodes (Fig. 19b) [175].

Traditionally, optimization techniques intended to design form as a function of material, while the new approach emphasizes the design of material as a function of form [207]. The development of AM technologies will potentially allow one to customize material properties, specifying internal material distribution over the volume, according to particular functions responding to a great variety of purposes.

6. Research challenges and conclusions

AM is evolving as a transformation technology for the construction sector, allowing architects and engineers to design more complex geometries. Firstly, some groups adapted existing systems (extrusion or binder jetting processes) to print concrete or polymeric construction elements. In most cases, these elements were produced off-site and assembled on-site. Gradually, medium and large-scale systems have been developed focusing more on on-site applications. More technologies need to be developed using in-situ resources.

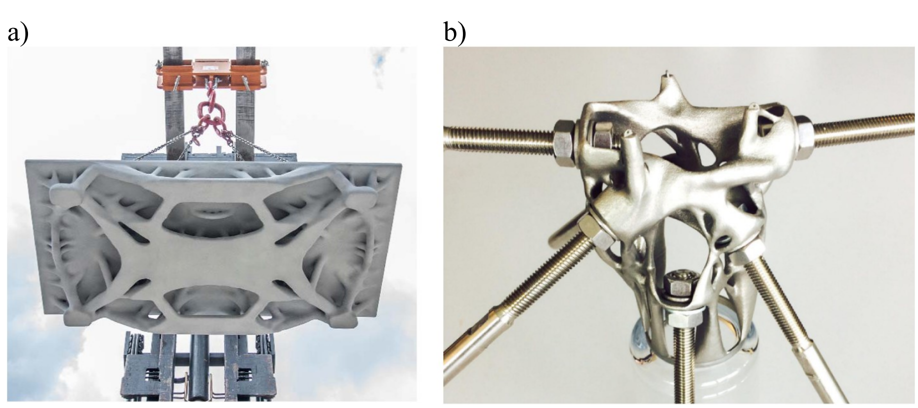


Fig. 19. a) Ceiling slab prototype produced using a 3D printed sandstone formwork [170], b) Optimized metal structural building element produced using AM [175].

To improve the printing process, the fresh properties of the printable construction materials must be defined as the hardened properties are fundamental to predict the stability of the printed components. From the fabrication viewpoint, key challenges include:

- printing time must be reduced to avoid premature solidification of the printed materials and clogs inside the 3D printing machine;
- for multi-material deposition, multiple-print heads or multiple-gantry systems/robots may be involved to accelerate construction time. In this case, collisions between print heads should be avoided;
- deposition process must not exceed a critical limit to guarantee a good interlayer adhesion, while lower printed layers should be able to support upper ones;
- deposition flow rate must be precisely controlled (the material printing flow should start and stop at time) to avoid material accumulation at specific areas, such as sharp corner areas, due to changes in the print head moving velocity;
- finishing operations must be considered in the production process since most of the current technologies print elements with a rough appearance. The use of formative and subtractive technologies can be used to minimize the stepping effect;
- a real-time feedback of the printer is fundamental to correct the geometry and appearance of the printed part, enhancing this way its quality.

Novel materials should be tested particularly using reinforcements (steel, fibers, fiber meshes, etc.) to improve structural safety and reliability. On the other hand, the use of smart materials, such as shape memory materials and self-healing materials, together with embedded sensors, will make buildings responsive to multiple stimuli adapted to environmental changes.

There are limitations to produce optimized material components in terms of shape/topology and material composition. In traditional construction several heterogeneous components respond to one purpose each, while functionally graded elements address multiple functions. Structural and functional properties can be enhanced using non-homogeneous, functionally graded materials with a continuous spatial change in properties, requiring fewer resources and producing less waste.

The development of new construction materials for AM requires further research in terms of materials testing and characterization standards, structural design requirements, as well the incorporation of building codes and standards, and the standardization of construction practices.

Producing large non-supported structures (roofs) or voids (windows, doorways, etc.) is still a big challenge. Vertical or non-horizontal printing with fast curing materials can be used for extrusion, a technology already developed for metal printing. The use of robotic-assisted printing systems for building repair application, not fully explored so far, as well exploring collaborative working with other robots or drones to assemble printed parts or apply coating materials (i.e. painting), will be a major trend in the future. Conversely, automated machines can perform hazardous and dangerous works reducing the number of injuries and fatalities in construction sites. AM can positively impact the construction industry provided it is accepted by construction stakeholders, though its economic feasibility must be considered. Today, its costs might be higher than those of traditional construction techniques, but it will be an added value for a modernized construction industry, opening new opportunities for innovative business models. Cost efficiency and current technological limitations are the key criteria to assess its future potential.

The construction industry must adopt technological innovation to respond to a fast-changing world. The digital revolution and the shortage of skilled construction workforce are two critical issues accelerating this transformation. The rapid expansion of advanced technologies, such as IoT, BIM and other digital systems are empowering a new digitalized construction industry, the so-called construction 4.0, which promise to increase construction productivity, quality, cost and resource-efficiency.

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