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Review

Extrusion-Based Additive Manufacturing of Concrete Products: Revolutionizing and Remodeling the Construction Industry

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Abstract: Additive manufacturing is one of the main topics of the fourth industrial revolution; defined as Industry 4.0. This technology offers several advantages related to the construction and architectural sectors; such as economic; environmental; social; and engineering benefits. The usage of concrete in additive technologies allows the development of innovative applications and complexity design in the world of construction such as buildings; housing modules; bridges; and urban and domestic furniture elements. The aim of this review was to show in detail a general panoramic of extrusion-based additive processes in the construction sector; the main advantages of using additive manufacturing with the respect to traditional manufacturing; the fundamental requirements of 3D printable material (fresh and hardened properties), and state-of-the-art aesthetic and architectural projects with functional properties.

Keywords: concrete additive manufacturing; construction; architecture; recycled waste material; rubber tire; environment; sustainability

1. Introduction

As one may know, construction is one of the largest industries in the world, which contributes globally to around 13 percent of the global gross domestic product (GDP). The usability of resources in the construction industry is astoundingly high and itself devours fifty percent of the world's overall resources. Moreover, the construction industry has traditionally been extremely averse to change and strongly adheres to traditional values, weakness in innovative construction, and lowliness in productivity. However, nowadays, companies are turning towards modern technology and boosting innovation that is taking place in design, engineering, maintenance, and operations as well as infrastructure, architecture, urban furniture, industrial molds, artificial intelligence, and sculpturing.

Additive manufacturing represents a new horizon in the field of concrete and cement-based materials. The research activity on additive manufacturing in the construction sector involves the development of two types of technologies: powder-based and extrusion-based.

In powder-based techniques (also called binder jetting), a binder solution is selectively deposited onto the ceramic powder bed (about 5–10 mm thickness) through a print nozzle, bonding these areas together to form the pre-designed solid part one layer at a time. The final object is removed after a specific drying time and excess powders are eliminated by an air jet [1,2].

Over the last few years, some construction technologies, based on powder printing, have been designed. The main examples are the D-shaped technique developed by Cesaretti et al. [3] and Voxeljet's Binder Jetting technology developed by Voxeljet Company [4].

These techniques are suitable for the production of complex-shaped construction components with a high print resolution, a high degree of geometric freedom, and reasonable manufacturing speeds in line with industrial demand [1,5]. However, the process is an emerging strategy and therefore still being optimized. The main criticalities of the technique concern the limited amount of cement materials on the market that can be used in powder-based printers, the difficulty in introducing structural reinforcements, and the need to perform several post-manufacturing operations (such as infiltration of binder solution or additional curing steps) that can adversely affect production times [1,5].

Analogous to the fused deposition modeling (FDM) method, extrusion-based additive manufacturing of concrete occurs when "printable" cement-based material is extruded through nozzles made of different sizes to form a layered structure [1], as presented clearly in Figure 1.

Figure 1. Extrusion-based additive manufacturing of concrete: deposition process. (Reproduced from Reference [6]).

Over the last twenty years, many research teams (both industrial and academic) have based their studies on the potential of extrusion-based additive production for construction applications. The main aspect that emerges from the predicted works is the analogy regarding the steps that lead to the final print product. Usually, the printing process involves a software part and a hardware part (Figure 2). The first is related to the use of 3D software, such as AutoCAD or SolidWorks, to model the object. The 3D design of the prototype is sliced (with the help of specific software) to define the size of each layer and subsequently converted to G-code format, which represents the machine language recognized by the printing device. The hardware part consists of an extrusion system (which deposits the material layer by layer), a material delivery system (which sends the material to the print head through a pumping system), and a controller (monitors the printer and pump according to the design of the final object) [7].

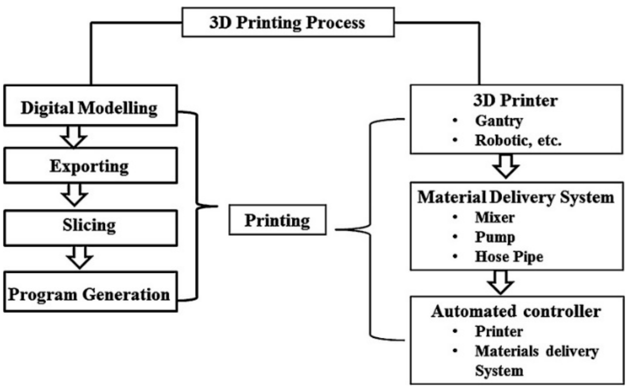

Figure 2. Additive manufacturing for construction industry (Reproduced with permission from: [7], Archives of civil and mechanical engineering; published by Science Direct, 2018).

The fundamental difference among the various printing technologies concerns mainly three aspects: (a) design of the printing apparatus, (b) composition of the concrete, and (c) technological applications of the final products. Table 1 below shows a complete overview of the main additive manufacturing technologies for construction and architectural sectors.

Table 1. Major additive manufacturing technologies for construction in the industrial and academic contexts.

3D printer	Type	Material	Country	Informational Reference
Constructions 3D	Robotic arm	Concrete/Earth materials	France	[8]
ICON Vulcan II	Gantry system	Concrete	USA	[9]
Kamer Maker	Robotic arm	Recycled/Bio-based	Netherlands	[10]
WASP Crane	Delta system	Concrete/Earth materials	Italy	[11]
Apis Cor	Robotic arm	Concrete	Russia	[12]
SC3DP Mobile robot	Robotic arm	Mortar/Geopolymer cement	Singapore	[13]
Contour Crafting	Gantry system	Concrete	USA	[14]

1.1. Design of the Printing Apparatus

Most concrete printing apparatuses are based on a robotic arm connected with the material storage system and moved through the appropriate software system. The print nozzle is attached to the robotic arm and is connected to the concrete mixer through a hose pipe. A pumping system allows the mix to be transported from the mixer to the deposition head. Some examples of this type of technology are Apis Cor and Singapore Centre for 3D Printing (SC3DP). The difference among these manufacturing systems is related to the apparatus design and the category of use.

Apis Cor [15], one of the creators of the first 3D-printed houses, describes in detail the technical features for site printing. The size of a standard cross-section of a printed layer needed is 2.5 × 2.5 cm, the current version of the construction 3D printer covers an area of 132 m^2 and the dimensions of the machine (i.e., "Apis Cor 3D printer" (Figure 3a)) in folded state is 4 × 1, 6 × 1, and 5 m and 2 tons of weight. As for accuracy, if the printing process complies with all the technical specifications, precision is up to 0.5 mm. The printer is capable of extruding at speeds up to 16 cm/s. Printer speed is automatically calculated using embedded software, and it depends on the printing path. Singapore Centre for 3D Printing (SC3DP) has developed two types of printing devices: a four-axis gantry and a six-axis robot (Figure 3b). Their use depends on the complexity of the product to be made: the first is mainly intended for large-scale prints while the other is for the creation of more complex shapes due to the fact of its six-axis rotational ability. The SC3DP printing devices grant greater degrees of freedom in the manufacturing process than Apis Cor technology but allow small-scale additive construction and, thus, better suited to the development of building components [16].

(a)

(b)

Figure 3. (**a**) Apis Cor 3D printer (Reproduced from [12]) and (**b**) SC3DP six-axis robot (Reproduced with permission from: [16], Virtual and Physical Prototyping; published by Taylor & Francis Group, 2017).

In addition to robotic arm-based systems, there are two other types of technologies: a gantry system (e.g., Contour Crafting and ICON Vulcan II) and a delta system (e.g., WASP Big Delta).

Gantry systems are crane-like manufacturing apparatuses that can be transported in specific trailers and allows the pre-designed structure to be developed directly at the construction site. The printer is equipped with a rotating print head (single- or multi-nozzle) combined with a hose connected to a mixer pump. The printer head is fixed on a vertical arm that is controlled by a four degree-of-freedom mainframe system. The manufacturing process is based on two approaches: formwork additive manufacturing and walls additive manufacturing.

The first approach (typical of the Contour Crafting printing system) involves combining two types of processes: extrusion and filling. The extrusion process allows for depositing two layers of cementitious materials to generate a formwork [14]. Printed formwork is simpler than the traditional design. A traditional concrete wall form typically consists of sheathing, studs, wales, ties, and bracing. The fresh concrete is confined to the sheathing and places a lateral pressure on the sheathing until the concrete is cured. Contour Crafting formwork is built using a printable mortar and secured with U-shaped tie rods. Compared to the conventional system, formwork developed through additive manufacturing involves the use of only two components: sheathing and tie. The sheathing is created in position by adding mortar continuously according to the pre-defined material deposition sequence; the ties are inserted at the sheathing locations. The advantage is that the formwork, made by additive manufacturing, can be built without using separate formwork materials resulting in economic benefits (lower production time and costs than traditional construction) and architectural advantages (greater design freedom) [17]. The filling process can take place through pouring or extrusion to achieve the core of the structure. Additional interventions are performed to improve the surface finish and mechanical integrity of the printed artifact. The result of the manufacturing process is a hollow wall filled with cementitious structural material. Research activities in the field of Contour Crafting technology led to the development of a vertical wall prototype 1.5 m long and 0.6 m high [14].

A walls additive manufacturing approach is more sophisticated and faster than the Contour Crafting process, as the printing apparatus allows one to develop the pre-designed building directly without the need for formworks, then through a single-step deposition process [18]. Typical examples of construction processes based on a walls additive manufacturing approach are ICON technology and WASP technology.

The ICON Vulcan II (Figure 4a) is a printing system designed and developed by a construction technology company located in Austin (USA). The machine is 3.45 m high and can print surfaces up to 8.5 m wide. Linear printing speed is about 12–17 cm/s. The printer is associated with an integrated tablet-based operating system to control every aspect of printing operations [9]. This technology was responsible for the construction of one of the first low-cost 3D-printed housings with requirements in line with local building standards. The house (32 m^2 surface) was built in 48 h (for at 9000 Euro) and consists of a living room, a bathroom, and a bedroom. The vertical elements of the building were made by the overlap of printable concrete layers that form a double wall divided by an interspace with a reinforced structure. The roof, windows, and doors are the only items not printed but installed later. Future perspectives are related to the introduction of technological improvements to reduce costs and production time. The ICON company's main purpose is to provide a viable strategy for housing construction in the poorest regions (e.g., South America) for the homeless [19].

"*Delta*" systems are a set of printing plants developed by the Italian company WASP. The purpose of WASP is to develop eco-sustainable buildings and structures using natural materials such as soil or agricultural waste. Research on this technology has led to the design and implementation of two types of apparatuses: the WASP Big Delta Printer and the WASP Crane (Figure 4b). The Big Delta configuration is 12 m high and 7 m wide, assembled with 6 m modular arms. All the machine-components have a maximum length of 3 m so that they can be easily loaded on a trailer and transported. The engine and electronic parts have been designed to be powered by solar panels, allowing to minimize energy consumption (approximately a 60 V power voltage). The printer can work at a maximum speed of 40 cm/s, but the printing rate depends on the amount of material inside the extruder. The extruder can handle large amounts of material (up to 200 kg) but, to minimize the effect of mechanical vibrations during deposition, the weight is reduced to 40–50 kg. The design of the print nozzle is suitable for the deposition of mixtures containing long-fiber materials following the targets of WASP technology: the extrusion of construction materials based on raw terrain and straw optimized with natural or synthetic fillers. Using 40 tons of straw/clay mixture, the apparatus was able to print, in 20 min, a circular wall 2.7 m in length and 5 m in diameter for a total cost of about 50 Euro [20]. The WASP Crane is an evolution of the Big Delta system.

This is a collaborative modular manufacturing system consisting of the main printer unit that can be assembled in various setups depending on the print area and then the size of the architectural product to be built. The single module is made of a diameter 6.60 m and 3 m height, can be extended by adding traverses and printer arms generating an "infinite" digital manufacturing system. This construction strategy implies a potentially infinite printing area, as the individual modules can be reconfigured and can advance with a generative attitude depending on the growth and shape of the artifact [21]. One of WASP's main projects is "*GAIA*". The house was printed utilizing a natural mud blend produced using soil taken from a natural site, as well as waste materials from rice production, for example, chopped straw and rice husks. This project is the consequence of a restricted and upgraded utilization of agricultural assets, which through innovation has been transformed into a highly functional raw material. The mixture was printed layer by layer using the WASP Crane system, creating walls with vertical cavities inside, where these cavities then need to be filled with rice husks for thermal insulation. It took 10 days for the realization of the external casing (designed with the aim of integrating natural ventilation systems and thermo-acoustic insulation systems in only one solution), for a total of 30 m^2 of wall whose thickness is 40 cm and the total cost of the materials used in the wall structure was 900 Euro [22].

(a) (b)

Figure 4. (**a**) ICON Vulcan II (Reproduced from [23]) and (**b**) WASP Crane apparatus (Reproduced from [24]).

1.2. Composition of the Printable Mixture

As for the material aggregation and mixture used in the printing process, we can see that there is an important difference between traditional cement paste and printable mixture. Traditional cement paste comprises a blend of oxides of calcium, silicon, and aluminum. Portland concrete and comparable materials are made by warming limestone (a wellspring of calcium) with earth and granulating this item (called clinker) with a source of sulfate (most normally gypsum) [25].

The aggregation material in the 3D printer is similar but varies in composition from the traditional ones. Cement mixtures, suitable for additive manufacturing, must have appropriate rheological and compositional properties in order to ensure an optimal deposition process: ease of extrusion through the nozzle, maintaining the shape after deposition, good adhesion between the printed layers (in order to increase mechanical properties of hardened printing products), and satisfactory stacking without collapsing phenomena [26]. Besides, the curing of material takes place in the air (no molds or containment structures) and, therefore, it is necessary that the building components must not encounter relevant post-deposition deformations. However, even concerning to technologies based on the formwork additive manufacturing approach (such as Contour Crafting), the requirements described above are crucial, as the formwork is developed through a layer-by-layer deposition process of printable mortar [14].

The main differences between traditional cement mixtures and printable mixtures are related to two aspects: Aggregates size and water/cement ratio (w/c ratio).

The aggregates size is crucial regarding the pumping and extruding processes of the cement mixture. To minimize print nozzle obstructions and ensure proper mix fluidity, many researchers focused their studies on the design of fine particles-based mixtures (printable mortars) suitable with high-resolution print nozzles (up to 1 cm diameter). The optimal size of fine aggregates provides values of no more than 300 µm [18,27]. However, some of these mixtures are also characterized by a certain percentage of coarse sand (up to 2 mm size) [18,26]. This replacement is implemented to improve the strength of the mortar and reduce the shrinkage crack in the printed objects [18]. Several printing technologies use cement mix based on coarse aggregates (Ø > 4mm) [18,28]. The presence of the coarse fraction improves the mechanical properties of the material compared to the printable mortars but requires the use of larger print nozzles (approximately 2.5 cm diameter). This negatively affects the print resolution and aesthetic properties of the final product [18].

The water/cement ratio affects the mix flowability and the mechanical properties of hardened material. Maximizing the mechanical strength in the mix means minimizing the water/cement ratio. However, a certain water amount must be maintained to ensure the appropriate workability of the concrete. Besides, the mix in the system must be flowable but upon pouring must be buildable and able to hold itself and subsequent layers [29]. According to the above requirements, the mixtures suitable for additive manufacturing are made with water/cement ratios between 0.3 and 0.4 [18,27,29,30], lower values when compared with typical values for traditional mortars or concretes (0.53–0.55) [31]. Portland cement serves the same purpose as it does in a traditional mix, nonetheless, on different bases, hydrators and cement additives are added to advance hydration and help the item keep its shape. Furthermore, finely chopped binders are utilized to help reinforce the material and a fluid component is splashed through the ink stream to help blend the material [32].

According to the additive manufacturing process, the final object shows a layered structure and the presence of an interface zone can be a source of mechanical weakness. To minimize the cracks or collapse of the object, the mixture can be optimized with the addition of fillers or reinforcement materials. The aim of this strategy is also related to obtaining better performance as printability, insulation, and water absorption. Guowei Ma proposed a printable cement mixture optimized with the addition of a certain percentage of copper tailings to replace the sand to improve the mechanical performance of concrete [33]. Besides, another possibility is working on the addition of fillers as crumb rubber, due to the fact of its advantages on toughness resistance, insulation, water absorption, and excellent machine performance (printing performances related to the quality of aggregation) [34]. Several academic and industrial research teams based their work on the development of low-environmental printable cement materials, as geopolymer mortars, for both small-scale [13,35] and large-scale applications [36]. Geopolymers are inorganic materials with chemical compositions similar to zeolites but with an amorphous structure. Typically a geopolymer is obtained by the combination of a powder of an alum-silicate material (industries by-products such as fly ash, slag, micronized recycling glass, etc.) with a (relatively concentrated) solution of an alkaline silicate (usually Sodium or Potassium). The material consolidation reaction takes place at room temperature and, depending on the preparation method, these mixtures can exhibit technological properties (mechanical, chemical, and thermal properties) superior compared to Portland cement. Interest in the use of this type of cement mixture is mainly related to environmental reasons: the absence of toxic substances and the reduction of CO_2 emissions [13].

2. Properties of Printable Mixture

Printable cement mixture must be formulated in such a way that both fresh and hardened material meets appropriate properties. The choice of the optimum fresh composition depends essentially on four parameters: extrudability, flowability, open time, and buildability [29]. The hardened performance includes mechanical properties such as compressive, flexural, and bond strength [27]. Therefore, it is necessary to find the right balance between mechanical properties and mixture printability.

2.1. Fresh Material Properties

The concrete mix must be intended to meet certain essential criteria that have an immediate relationship with the system of printing the concrete material. In this manner, it is basic to guarantee a reciprocal association between the mixture and printing machine [29].

- Extrudability refers to the material's ability to be pumped out smoothly through an extruder without any disruption/clogging in the pipe flow. This parameter is not an intrinsic chemical or physical property of the mixture but rather a specific property of a complex printing process. It depends on the mixture composition, the nozzle geometry, the extruder design, the pumping system, and some process parameters [37]. A deposition without discontinuity or deformation (due to the drainage phenomena of the fresh mixture or obstructions of the nozzle by the concrete solid fraction) implies a good extrudability [33]. The literature highlights that the main methods used to determine the extrusion of printable mixtures allow a qualitative evaluation of this parameter. Generally, three tests can be identified: the ram-extruder method [38], penetration resistance method [39], and vane rheometry [26]. In the ram-extruder approach, the force required to extrude material through a nozzle is a measure of its extrudability. Experimental analysis is supported by mathematical models that take into account different variables related to the deposition process: friction between cement material and the extruder's inner surface and mixture rheology and mechanical properties of the aggregated [38]. In the Vane test, extrudability is evaluated concerning Bingham parameters and other flow properties. According to these measurements, materials possessing very high (static) yield stress are difficult to extrude and may result in discontinuities during the extrusion process [26];
- Flowability refers to the easy-flowing paste passing through the printing nozzles without discontinuity [29]. The slump test is the experimental procedure mainly used to evaluate the flowability of the mixture, as it provides immediate results and is easy to run. A metallic cone, with well-defined geometric characteristics, is filled with the fresh cement mixture. The magnitude of the height decrease of the paste, after the removal of the cone, allows quantifying the fluidity of the material. A larger slump value corresponds to a greater flowability [33];
- Buildability refers to the ability of the printed concrete layer to hold the layers above other layers without crumbling. This property can be evaluated either by quantifying the number of layers stacked up to the collapse of the structure [33] and by considering the degree of deformation of the stacked layers of cement material as a result of the mass of the new layers of extrudate [40]. One of the variables, related to the printing process, which significantly affects this material parameter is the paste age (or rest time). Paste age is defined as the time that elapses from the mixing phase of the printing material at the beginning of the deposition. This parameter affects the viscous properties of the fresh material and then the adhesion between one layer and the other. Longer paste age promotes an easier transition of material from the fluid state to the plastic state and therefore greater stiffness of each layer. In the condition of optimal buildability, the resulting layered structure will be characterized by a greater number of layers poorly deformed compared to the dimensions of the nozzle. However, by extending the paste age, a worsening of the mechanical integrity of the printed structure occurs. The higher stiffness of extruded filaments reduces the interfacial adhesion among two layers, resulting in the formation of unwanted voids [41];
- Open time refers to studying the change of concrete flowability with time. The aim is to guarantee that each printed layer can to hold itself and stay harden when poured, but then remain fluid enough to bond with the layer above it and not to be turned into a different structure. This parameter can be evaluated by rheological measurements on the mix (by monitoring variations in material

viscosity) [27] or by extruding the filament and measuring the time at which it breaks [29]. Open time needs to be set according to two factors: the total printing time and the capabilities of the printing device. Rheological tests allow to monitor how the shear strength of the fresh material varies with the time (using a vane shear apparatus). This property is established when the shear strength reaches values that make the workability of the material worse (related to a difficulty in the printing process) [27].

2.2. Hardened Material Properties

The importance of testing the physical and mechanical properties of hardened material is related to the particular layered structure that extrusion-based additive manufacturing produces. If interfacial adhesion among layers is not optimal, voids are created (Figure 5) that act as sources of mechanical weakness for the structure [27].

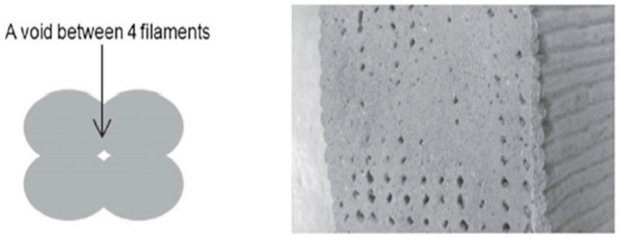

Figure 5. Voids generation in the concrete structure. (Reproduced with permission from: [27], Cement and Concrete Research; published by Science Direct, 2012).

Moreover, depending on the structural strength of the printed layer, maximizing the compressive strength in the mix implies limiting the water–concrete proportion yet inferring a decrement of the workability. The presence of a layered structure implies different mechanical behavior depending on the direction of loading, as shown in Figure 6.

The following graph shows the results of the compressive test of printed samples in various loading directions (D1, D2, and D3) done between day 7, 14, and 28 and the comparison with "control" sample obtained by traditional casting. The results showed an anisotropic mechanical behavior of printed samples but the compressive strength was similar to traditional concrete. In order to minimize this variable's mechanical behavior and to guarantee the structural integrity, it is important to add to the mixture mechanical reinforcements or to work on the rheological properties of the fresh mix [7].

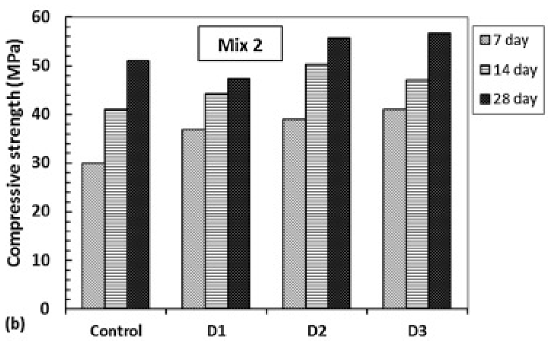

Figure 6. Compressive strength of 3D printed samples at different direction loading. (Reproduced with permission from: [7], Archives of Civil and Mechanical Engineering; published by Science Direct, 2018).

2.3. Fundamental Requirements of Printed Applications

The actual additives technologies that works in the building sector, base their applications on fundamental requirements for print quality such as no cracks and holes, shape stability such as self-sustaining layers and no collapse, a printability window with a sufficient time frame for material extrusion, a high degree of compaction achieved without vibration, durability and absence of cracks induced by shrinkage, in addition to interlayered adhesion forming structural integrity where overlapping layers create high adhesive strength [15,32].

3. Pros, Cons, and Future Perspectives of 3D Concrete Printing in Comparison with Traditional Construction

This chapter highlights the benefits, criticalities, and potential of additive manufacturing applied to the construction sector. The following aspects are supported by case studies and examples of applications in the construction and architectural contexts. Through discussion and analysis of the case study projects, and the methods used to design and fabricate them, initial conclusions can be drawn related to the potentials and limitations of construction using additive manufacturing.

3.1. Pros of Additive Manufacturing in the Construction Sector

The potential benefits of additive manufacturing as related to the aspects of construction and architecture are summarized in the following points [30,38]:

- Cost reduction: Additive manufacturing is a construction technology that does not use a conventional formwork. In traditional construction, formwork represents 35–60% of the overall cost of the concrete structure;
- Reduction of environmental pollution: In the course of development, there is no waste or debris which would require expulsion from construction sites and recycling;
- Reducing the quantity of the workforce associated with development and, therefore, reducing the cost of servicing staff (e.g., transportation, cooking, costs for garments), protection, charges, emergency clinics, etc. Moreover, innovation can essentially diminish the expense of the development of structures with one of a kind engineering. Three-dimensional printers are not restricted to rectilinear shapes;
- Reduction in manufacturing time: 3D printer does not require a break for lunch and weekend, it can work without interruption and faster than human labor;
- Improving the quality and unwavering quality of a structure by taking out the human factor: staff insufficiency and development errors. This aspect is also related to the decrease in injuries and fatalities in the workplace;
- Reduction of time and work for the establishment of utilities because printed structures incorporate a space for laying building correspondences, engineering communication, and other equipment;
- Architectural freedom: a 3D printer based on 3 degrees of freedom (x, y, z) manufacturing. This feature allows the development of highly complex shapes and geometry (Figure 7). Thanks to this feature, additive manufacturing allows the possibility to realize unconventional building elements (e.g., holes, porous structure, curved structure) with improved engineering and aesthetic properties. While traditional manufacturing is based on the use of formwork or molds as shown in Figure 8. Moreover, this aspect allows the realization of buildings with "standard" shapes with no possibility to work on the morphology of the element.

Figure 7. Additive Manufacturing as Walls 3D Manufacturing and Bricks 3D Manufacturing. (Reproduced with permission from: [16], Virtual and Physical Prototyping; published by Taylor & Francis Group, 2017).

Figure 8. (**a**) Traditional manufacturing as walls manufacturing (Reproduced from [42]) and (**b**) bricks manufacturing (Reproduced from [43]).

Case Study: Structural Wall Elements with Functional Properties

Design freedom and the possibility of producing highly complex shape components, compared to traditional casting processes, are the two most interesting features offered by additive manufacturing. In the construction and architectural contexts, this technology would counter the financial constraints related to the production of unconventional geometry molds or formworks that can be used in traditional manufacturing methods. The development of geometrically complex molds implies large quantities of waste materials and significant slowdowns in production. To highlight the feasibility of additive manufacturing in the production of large-scale building components, two examples relating to the development of functional structural elements are described. "Functional" means that it is possible to modulate the shape and geometry of these components to optimize some fundamental properties for the energy efficiency of buildings, such as mechanical strength, thermal insulation, and acoustic damping. The projects were curated by the Gosselin et al. research team [44]. Prototype manufacturing was carried out using a printing system based on a six-axis robotic arm using a printable mortar (ultra-high performance concrete) as a building material.

The first example is about the design of a multifunctional wall element aimed at optimizing the thermal properties of the structure to which it is intended. The element consists in an absorptive formwork to be filled with insulating foam for thermal insulation. The complex shape of the component (bi-sinusoidal geometry) has been studied and is designed appropriately to reduce the flow of heat through it. The resulting structure consists of internal cavities that optimize thermal insulation (thanks to the reduction of thermal bridges) while maintaining optimal structural properties. The thermal performances of the element were inferred by applying a complex mathematical model for the study of thermal transport properties (described in detail in Reference [44]) and compared with the results obtained in the case of a traditional design formwork. The results showed that bi-sinusoidal geometry provided a 56% increase in thermal insulation performances compared to conventional geometry. It took 12 h to manufacture the component (1360 mm × 1500 mm × 170 mm size for 450 kg weight).

Another example of a functional printed structure is an acoustic damping wall (Figure 9). This application is based on cavities of different sizes and shapes to form a vertical structure. This particular conformation gives the possibility to obtain acoustic damping. The cavities produce a friction effect when a sound wave passes through them and this phenomenon improves the sound absorption. The acoustic absorption properties are related to the size and shape of the cavities and on the type of printed material, knowing that the produced element is sized roughly 650 mm × 650 mm × 300 mm and made of 26 layers. There are no studies in the literature regarding the acoustic performances of the damping wall.

Figure 9. 3D printed acoustic damping wall (Reproduced with permission from: [44], Materials and Design; published by Science Direct, 2016).

The projects described above highlight the peculiarity of additive manufacturing to exploit architectural freedom to create complex products (unthinkable using conventional methodologies) with pleasant aesthetic characteristics and with interesting engineering properties. To complete the discussion on the benefits of additive production applied to the construction sector, it is interesting to show a comparative analysis of the costs associated with traditional and additive manufacturing in the implementation of unconventional building components. Specifically, the study conducted by Garcia de Soto et al. [45] highlights the distribution of labor, materials, and equipment expenses (in euros) for curved-shape concrete walls made with traditional manufacturing (formwork based) and with additive manufacturing (robot system based). The comparison of the costs distribution associated with the two construction methodologies is shown in Table 2.

Table 2. Traditional manufacturing versus additive manufacturing: the distribution of labour, material, and equipment costs for concrete curved wall construction. (Data Reproduced from [45]).

Construction Method	Labor	Material	Equipment	Total Cost
Curved Wall/Traditional	1,071,466 €	3,697,863 €	136,210 €	4,905,539 €
Curved Wall/Additive Manufacturing	1,077,926 €	721,698 €	287,764 €	2,087,388 €

The construction of complex structures using traditional methods implies a considerable increase in costs of approximately 75% compared to additive techniques. The production of formworks suitable for the development of unconventional elements requires the involvement of more labor (e.g., carpenters, operators, cement finishers) and a greater amount of building material, increasing expenses, waste, and production time. Not only that, formworks also require a significant amount of pre-pour concrete preparation, implying an additional release of CO_2 into the environment [46]. Additive manufacturing is expensive for initial setup (costly automated machines are not always financially feasible) [47] but provides a cost-effective and sustainable alternative solution for the construction industry.

3.2. Cons of Additive Manufacturing in the Construction Sector

Critical issues of additive manufacturing applied to the construction sector are generally summarized in two aspects: technological criticality and certification issues.

As discussed above, additive manufacturing of cement materials involves several technologies that are based on specific approaches (robotic arm-based systems, formwork additive manufacturing, and walls additive manufacturing). As a result, there will be specific technological limitations associated with the strategies described above. This does not allow us to identify an optimal construction method, but the technology will have to be selected based on the type of application to which the final product is intended. For instance, some significant disadvantages have been identified regarding Contour

Crafting technology [1,44]: Production of 2.5D topologies (a vertical extension of a planar shape), difficulty implementing the deposition system, and issues regarding the structural integrity of the printed formwork (due to the hydrostatic pressure exerted by the filling cement material). In crane-like manufacturing apparatuses, which are based on a formwork-free approach, the disadvantages can be traced back to the following aspects [1,44,48]:

- Architectural freedom and dimensional tolerance are limited by the size of the printing frame;
- In the most sophisticated dual extruder systems (i.e., using a support material to create overhangs and other freeform features [49]), there is less efficiency, cost-effectiveness, and flexibility in the process. The additional deposition system requires more maintenance, cleaning, and control instructions.

Robotic arm-based printing technologies guarantee greater resolution and design freedom compared to the technologies mentioned above. However, their performances are enhanced in the case of small-scale applications and for the development of geometrically unconventional elements. Garcia de Soto et al.'s [45] comparative study showed that using this approach to produce "standard" structural elements is not a cost-effective method. In this case, traditional manufacturing is a better solution, especially in terms of materials and equipment used. Table 3 shows a comparison of the distribution of costs related to the construction of a straight wall through a traditional manufacturing and robotic arm-based printing apparatus.

Table 3. Traditional manufacturing versus additive manufacturing: distribution of labour, material and equipment costs for concrete straight wall construction (Data Reproduced from [45]).

Construction Method	Labor	Material	Equipment	Total Cost
Straight Wall/Traditional	355,657 €	149,815 €	135,047 €	640,518 €
Straight Wall/Additive Manufacturing	9859 €	694,631 €	284,951 €	1,965,482 €

Certification issues are closely related to testing and evaluation standard methods for cement materials used in additive manufacturing. One of the main critical points of the technology, applied to the construction industry, concerns safety. In fact, the standard procedures used to study and test the mechanical and structural performance of traditional building materials are not easily adaptable to cement materials suitable for additive manufacturing. This aspect can be traced back to the rheology of printable cement mixtures (very different from traditional mix) and the mechanical anisotropy of the final product (related to the layered structure generated by layer-by-layer extrusion). Besides, at this time, there is a complete lack of basic and unified standards and regulations that are needed to establish the mechanical behaviour and structural integrity of specimen, components, and structures made by additive technology.

Case Study: Certification of the Structural Integrity of a Bridge Made by Additive Manufacturing

The description of this case study aimed to highlight one of the most difficult challenges of additive manufacturing in the construction sector: the certification of safety and integrity of structures. This aspect is of fundamental importance to promote the public use of these applications and not to consider them only as simple exhibition prototypes. This paper discusses the complications encountered during the construction of a mortar printable bridge in a public traffic network and the strategies adopted to certify its structural properties. The main issue for the implementation of the infrastructure is the lack of codes to test the structural properties of printable concrete.

The bridge project is the result of research by the Eindhoven University of Technology [50] and is part of a renewal intervention of an existing bicycle track called Lieve Vrouwensteeg.

To optimize the cross-section and minimize residual stressors, it was decided to make the component not by printing it in one piece but by assembling multiple printed elements. The cross-section of the bridge elements consisted of a series of connected "bottle" shapes, alternatively positioned upside down. This type of shape has been specially designed to optimize bending strength and resistance to shear stress, highlighting the peculiarities of additive manufacturing to give functionality to the component by working on complexity geometry. The bridge consisted of six elements, for a span of 6.5 m and a width of 3.5 m. Manufacturing process, printing system specifications, and assembly steps are described in detail in Reference [50,51]. The purpose of this treatment was to show the type of experimental procedure used for the certification of the bridge under Dutch building regulations. In this regard, a two-step procedure was performed:

(1) Printable material testing;
(2) Structural tests on a scale model (1:2) of the bridge;
(3) Structural tests at the site on the actual bridge.

The material used in the research was a custom-designed printable mortar considering the characteristics of the printing apparatus and therefore not compliant with the standards designations. The strength of the printed concrete varied depending on the load direction compared to the print direction. Given this, the mechanical tests were performed in three independent perpendicular directions.

Structural tests on the scale model were destructive mechanical tests needed to prove that the structural codes, valid in the case of traditional cement materials, were adaptable and also conformed to the printable material used in the work.

The final non-destructive full-scale test was performed in situ to guarantee that the bridge would behave as expected and be structurally safe. This type of test (commonly used in the Netherlands for structural characterization of existing infrastructure) was adapted to the bridge analysis to determine the load-bearing capacity. The bridge was loaded with 10 containers filled with 500 L of water (for a total load of 57 kN).

In consideration of the results on scale testing and final full-scale test, the bridge was considered to comply with the Dutch building regulations and opened in October 2017. An image of the bridge in operation mode is shown in Figure 10.

This case study showed that adapting existing structural codes to the certification of printed designs implies a much more complex testing campaign than the traditional validation method (testing on scale prototypes and mechanical characterization in function of the load direction). Besides, the directives performed for bridge safety certification comply with Dutch legislation and, therefore, may not be shared in other social contexts. This is a consequence of the lack of internationally shared regulations.

Figure 10. 3D printed bicycle bridge developed by Eindhoven University of Technology (Reproduced from [52]).

3.3. Future Perspectives of Additive Manufacturing in the Construction Sector

Nowadays, progression in the field of additive manufacturing has increased rapidly due to the demands for ecological, environmental, low-cost, and high-speed aspects during production, as well as design freedom and a reduction of construction waste. The demand for architectural and design freedom is increasing progressively and challenges architects to bring visionary ideas into reality. However, putting these modernized designs and complex structures without limitations into effect using steel and concrete construction, places large requirements on innovation in the field of concrete. Three-dimensional concrete printing can bring imagination into reality with automation, lower costs, and reduction in waste production during construction. Below presents an analysis of the future development of the 3D printing of concrete in detail [16,51,53].

3.3.1. Topological Optimization

Additive manufacturing offers significant build freedom that will make this technology suitable for the development of complex structural elements (e.g., doubly curved cladding panels, acoustic thermal insulator wall elements, hollow walls with corrugated internal structures) that are difficult to fabricate by conventional methods. Thanks to this feature, construction components can be designed to tune their properties according to the type of application to which they are addressed (weight reduction, improvement of mechanical properties, acoustic damping).

3.3.2. Technology Improvement

Optimizing printer design, studying optimal process parameters, and finding automated strategies for inserting structural reinforcements are the most interesting perspectives in additive manufacturing applications. Concerning the architecture of the printing apparatus, research is aimed at the integration of multi-nozzle deposition systems. Multiple nozzles can be integrated into conventional apparatus to print specific sections of the object (and thus speed up the production process) or to depose materials with different properties, enhancing the functionality of the product. However, the integration and assembly of multiple deposition systems is complex and requires proper planning [16].

The implementation of structural reinforcements is another major challenge for additive manufacturing. This requirement is related to the low tensile strength properties and ductility of the printable cement mixture which results in unenforceability in structural applications. Contour Crafting technology has developed a strategy to improve the capacity of printed structures that is based on creating voids in the component in which to manually insert steel bars [17]. However, this approach greatly limits the architectural freedom of the process. The insertion of strengthening materials could be implemented integrating a second extruder that, simultaneously with the deposition process, releases metal fibers to improve mechanical behavior of the component [16,53].

Finally, future studies will need to be based on careful selection and balancing of process parameters to ensure the best trade-off between product quality, production time, and production costs.

High buildability is related to a correct match between print speed and flow rate [16]. The printing speed affects the dimensional accuracy of the printed component [53]. Choosing the layers' thickness affects the generation of inter-layer voids (the effect can be minimized by decreasing the deposed thickness but this approach increases printing time) [16]. Therefore, the optimization of the process depends on the rheology of the printable mixture and the technological application of the final product [47].

3.3.3. Development of New Printable Materials

The design of a material, suitable for extrusion-based additive manufacturing, requires a highly complex research activity, as the properties of the mixture must be compatible with the type of printing apparatus and meet appropriate physical–mechanical requirements. In this context, research is focusing on the use of numerous raw materials to prepare printable mixtures to give additional functionality to the material. The addition of a polymer (e.g., polypropylene fibers [27–51]) or ceramic fibers (e.g., glass fibers [54], basalt fibers [30]) is a strategy being studied and aims to improve the flexural strength and cracking resistance of printed structures [53]. Besides, research is also focusing on more environmentally friendly solutions such as "green cement materials". "Green cement materials" are characterized by application of industrial wastes to reduce consumption of natural resources and energy and pollution of the environment [55]. Fillers, deriving from industrial waste (tire rubber [34], textile waste [56], paper pulp [57]), can be added in partial replacement of the aggregates to optimize several physical properties of the mixture such as density, thermal insulation, sound insulation, and damping of the mechanical vibrations. However, this strategy will require thorough studies related to the printing of the mixture, certification of structural performances, and optimization of the cement matrix–filler interface. The addition of chemical additives during preparation could confer specific rheological or functional properties to the mixture (such as self-sensing, self-compacting, self-healing, and self-cleaning) [53]. Finally, an important issue associated with the production of cement material concerns CO_2 emissions. In this area, research activity is focused on decarbonization strategies for the production of cement materials, for example with the development and optimization of geopolymer-based mixtures [13,35]. Potential methods to create a more sustainable mixture is to replace the concrete contents with other materials such as fly ash or recycle the previously used concrete aggregate [58].

4. Architectural Projects Done by 3D Concrete Printing

Figure 11 below clearly shows that a portable printer is a proficient operational unit. A brilliant machine that can be effectively conveyed to the site requires at least time and vitality to begin working in the field. It gets work done 100 percent as required. By "contracting" a printer for work, one frees a portion of their assets. One saves money on work costs, managing development squander, leasing development hardware and devices, saving time and energy as related to house insulation and installation. One printer can supplant an entire group of development specialists, sparing time without loss of value. However, according to "Apis Cor" one of the most important 3D concrete printing companies in the market presents in detail the cost of printing of 1 m^3 of finished building structure as it is composed of many factors, such as the configuration and thickness of the wall, grade of the mixture used, the location of the construction, etc.; therefore, the exact value can be calculated only on the basis of the building project. In this embodiment of a 1 m^2 wall, a thickness of 300 mm requires 0.093 m^3 of printing mixture. To date, the cost of construction is calculated to be 90 to 150 Euro per m^3 [59].

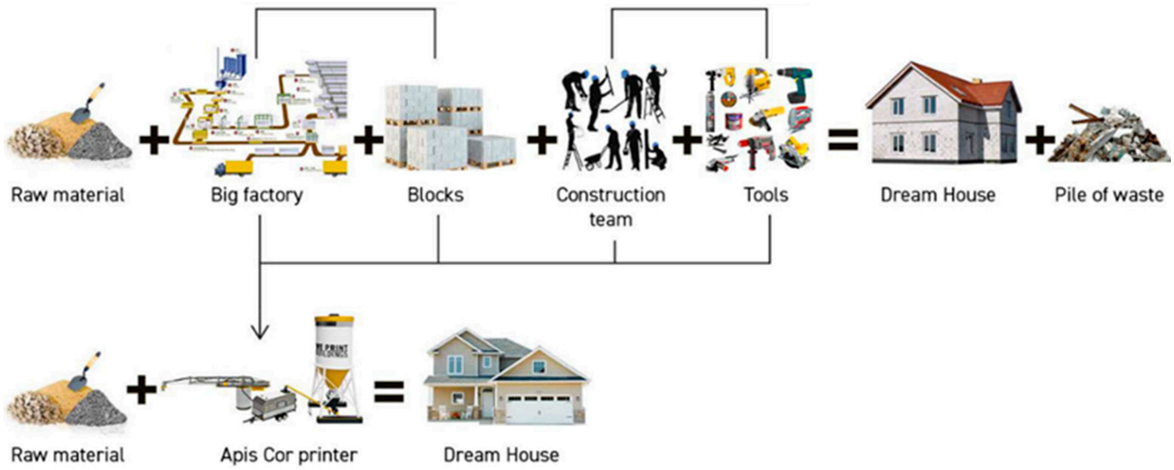

Figure 11. Additive manufacturing concrete building process (Reproduced from [59]).

In Figure 12, we can see several completed projects done using 3D concrete printing. Figure 12a shows the first functional office made by additive manufacturing: "The Office of the Future" (Dubai). Figure 12b shows "3D Housing 05 housing" in Italy. The building, designed by Arup and CLS Architects, was exhibited during a "Salone del Mobile" event. Developed by a compact printing robot, the home contains some of the advantages offered by additive manufacturing: decreased material waste, wide efficiency of the construction process, and reuse of end of life building materials. Moreover, Figure 12c, shows a "3D printed concrete castle" that took place in the USA. This architectural element was completed in two years and led the way for the use of additive manufacturing in the construction sector. Finally, Figure 12d, shows one of the projects carried out by Loughborough University researchers (UK). The British research team aimed to show the potential of additive manufacturing in the creation of functional components of highly complex shapes in a very short time.

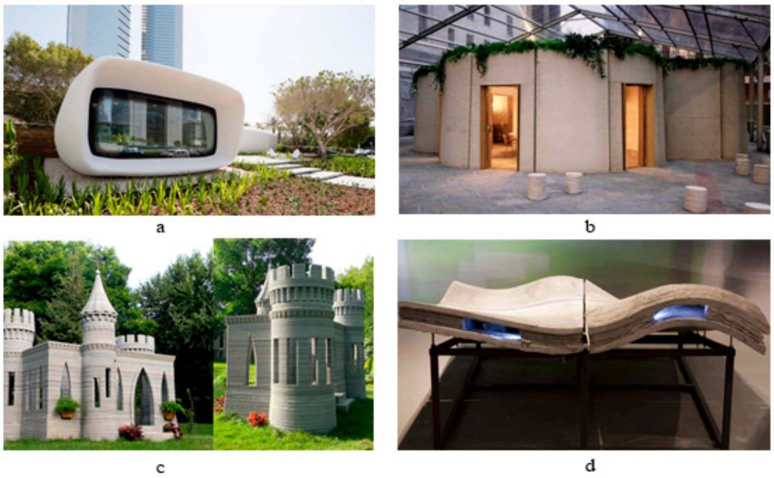

Figure 12. Several architectural applications and elements. (**a**): "The Office of the Future" (Reproduced from [60]). (**b**): "3D Housing 05" (Reproduced from [61]). (**c**): "3D printed concrete castle" (Reproduced from [62]). (**d**): "Loughborough University project" (Reproduced from [63]).

5. Conclusions

Extrusion-based additive manufacturing shows important advantages from structural, environmental, and architectural points of view. In this review, the main technological-engineering aspects, potentials, criticalities, and future developments of extrusion-based additive manufacturing applied to the construction industry were examined.

The introductory chapter described some additive manufacturing systems operating in the architectural and construction sectors. This section highlighted the differences among the various technologies regarding the printing apparatus, materials used, and the construction projects implemented or potentially achievable. In addition, a general description of the main differences between printable mixtures and traditional mixtures (related to rheological properties, the size of aggregates, and the addition of chemical additives or reinforcements) was shown.

The second chapter analyzed the properties of a printable cement material suitable for extrusion-based additive manufacturing. The properties of the fresh material are closely related to the rheology of the mixture and are selected based on two aspects: design of the printing apparatus and technological application of the final product. For this reason, the evaluation of these properties is mainly qualitative and depends on the complexity of the manufacturing process. The properties of the hardened material are related to its mechanical performances which, due to the layered structure induced by the deposition process, depend on the load direction.

Chapter 3 highlighted the benefits, limitations, and potential developments of additive manufacturing in cement materials. The main aspect that emerged from this analysis (considering also the case studies supporting each of these aspects) was the possibility of exploiting the relevant architectural freedom of this technology to confer, through the development of complex shapes and unconventional geometries, interesting functional properties to construction components. These elements can then be easily engineered by working on their morphology and then tuning the physical, thermal, acoustic, mechanical properties according to the type of technological application. In addition to this, there are socio-economic advantages over traditional manufacturing. However, basic and unified standards and regulations are needed for an effective and accurate assessment of the mechanical performances of samples, components and structures manufactured with 3D printing. This is essential to facilitate the validation process regarding the safety aspect and to allow the diffusion of printed products also for civil and urban use. Finally, future challenges in additive technology focus on three aspects: the study of innovative and functional shapes to be conferred on building products, the optimization of the printing process, and the development of new printable materials. The purpose of this research was to develop "bi-functional" solutions for the construction sector. "Bi-functionality" means giving the product specific physical and engineering properties through topological optimization and modification of the cement mixture with fillers or additives. In addition to this strategy, there was a careful analysis of the environmental aspect and the eco-compatibility of mixtures and their production method.

As is clear in Chapter 4, additive manufacturing has made important progress in the implementation of construction and architectural works. However, reaching the targets mentioned above would allow the technology to reach its full potential in the construction sector.

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