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Large-Scale Automated Additive Construction: Overview, Robotic Solutions, Sustainability, and Future Prospect

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Abstract: Additive manufacturing has drawn significant attention in both academia and industry due to its capabilities and promising potential in various sectors. However, the adoption of this technology in large-scale construction is still limited due to the numerous existing challenges. In this work, a comprehensive review of large-scale automated additive construction, its challenges, and emerging advances with a focus on robotic solutions and environmental sustainability is presented. The potential interrelations of the two topics are also discussed. A new classification scheme of available and emerging robotic solutions in automated additive construction is presented. Moreover, the vision of environmental sustainability is explored through three lenses: process, material, and printed large-scale structures/buildings. Finally, the current challenges and potential future directions are highlighted. The provided state of the art and challenges can be used as a guideline for future research on large-scale automated additive construction.

Keywords: additive manufacturing; large-scale construction; automated additive construction; robotic 3D printing; environmental sustainability

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1. Introduction

Additive manufacturing (AM), also known as three-dimensional (3D) printing, has drawn significant attention in different industrial sectors, including aerospace [1], soft robotics [2], automotive [3], electronics [4], medicine [5], and construction [6]. In this layer-by-layer manufacturing process, a wide range of materials, such as metals, polymers, ceramics, glass, and sand, have been used [7–9]. Among the several benefits of AM is the rapid fabrication of geometrically complex products at a relatively lower cost. According to the ASTM international committee [10], AM has been classified into seven categories: binder jetting, material extrusion, direct energy deposition, material jetting, sheet lamination, powder bed fusion, and vat photopolymerization. In the context of large-scale automated additive construction, also frequently referred to as additive construction, i.e., the adoption of AM techniques for large-scale construction, such as the construction of walls, buildings, and bridges under automated computer control [11], extrusion-based and powder-based techniques are recognized as the most promising processes [12]. Due to the automated nature of the AM process, the adoption of AM in construction not only leads to fewer errors, fewer waste materials, and a reduction in relevant costs, but also enables the construction of smart structures using functional material. Moreover, applications of AM in the building and construction industry can lead to a significant reduction in the global total carbon dioxide emissions.

Concrete is known as the most common construction material; it has been utilized over the years and is still used in modern buildings [13]. Based on the distinctive properties of concrete and its variants (e.g., compressive strength, fire resistance, and durability), it has been used in a diverse set of applications, such as offshore structures, residential buildings, bridge construction, dams, and driveways [14–17]. Since the consumption of more than 40% of the worldwide resources is associated with the construction industry [18], advances and progresses in this field can lead to large impacts and significant changes in different domains. For instance, optimization in construction projects has a great influence on energy consumption and climate change. Considering the capabilities and benefits of AM, it is expected that this technology can open up new opportunities for large-scale construction. Nonetheless, despite various attempts, research in the field of automated additive construction is still in its preliminary stages.

Due to the importance of automation in the construction industry and to enable future innovations in these areas, a review of the current literature is critical. Despite some available review papers on the topic [19–28], in this work, the authors aim to provide a comprehensive review of the existing relevant literature and emerging topics on large-scale automated additive construction with respect to robotic solutions and environmental sustainability. Moreover, discussions on the interconnections of the two topics of robotic solutions and sustainability in automated additive construction (currently not well addressed in the literature) are presented. First, an introductory overview of large-scale additive construction, its general applications, and its materials utilized is presented. Next, a new classification scheme of the robotic solutions in additive construction is presented based on available and emerging topics, followed by a review of the literature within each class. Third, the environmental sustainability research in additive construction is viewed from three different lenses: process, material, and printed structures. The process lens considers the environmental sustainability (e.g., energy consumption) of the process, including the adopted AM technology and the robotic solution/platform. The material lens categorizes the available studies based on the type of the construction material, while the lens of printed structures deals with post-construction sustainability. Finally, existing gaps and future research directions are highlighted. It should be noted that although the terms "automated additive construction" and "additive construction" are used interchangeably in the literature, the manuscript uses "additive construction" for consistency. Moreover, although the definition of sustainability is broad and can point to environmental, social, and economic impacts, in this manuscript, the term "sustainability" refers to environmental sustainability.

The rest of this paper is organized as follows: Section 2 presents the adopted systematic review methodology. In Section 3, a brief introductory overview of AM in large-scale construction and its evolution through the years is presented. Applications of robots in this field have been reviewed and summarized in Section 4. In Section 5, the state of the art on the sustainability and environmental impacts of additive construction is reviewed and studies are clustered into three groups. Next, in Section 6 current challenges and prospects are outlined. Finally, the conclusion is presented in Section 7.

2. Review Methodology and Paper Structure

This review aims to address the following research questions:

- Motivational research question 1: What robotic solutions have been found suitable for the purpose of additive construction and what are their advantages, disadvantages, limitations, and emerging challenges so far?
- Motivational research question 2: How does the current research tackle the environmental sustainability challenge in the domain of additive construction and what are the current emerging topics and limitations?

To answer the above questions, a systematic literature review is adopted to identify the literature with a focus on the papers published between 2000 and 2022. Two separate searches of the literature were conducted for each of the two aspects of robotic additive construction and sustainability in additive construction and were then filtered and studied. The majority of studies were found to be focused on only one of the above topics. The detailed steps of the search and selection mechanism are described as follows.

The scientific published works in different databases and libraries, including ScienceDirect, SpringerLink, ASME digital collection, Scopus, ACM digital library, Wiley online library, ASCE, and PubMed, have been reviewed. The adopted search keywords include but are not limited to "concrete 3D printing", "sustainability", "life cycle impact", "large-scale additive manufacturing", "robotic 3D printing", "automated construction", and their combinations (as shown in Figure 1). The search results generated over 500 documents, which were further narrowed down based on the title, abstract, and content. Among the search results, papers that were not relevant to this study were removed, and the published original research that was peer-reviewed and written in the English language was selected to review in this paper. Moreover, some of the excluded documented research works satisfying the following criteria were included to the search and have also been analyzed to identify challenges and future research directions:

(i) Pioneering studies in the field of additive construction published prior to the year 2000;
(ii) Advances on robotic AM with applications in the domain of additive construction (on a larger scale);
(iii) Advances on sustainable material with applications in the additive construction domain. The overview of the paper's structure per the above methodology is shown in Figure 2.

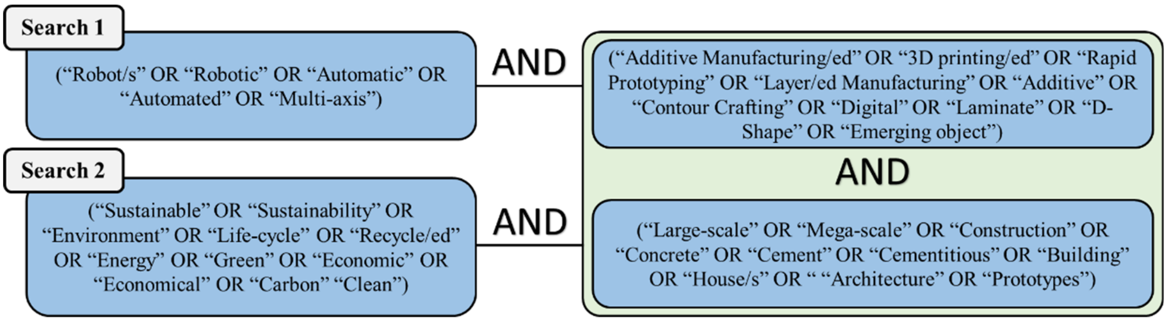

Figure 1. Selected keywords for the search process.

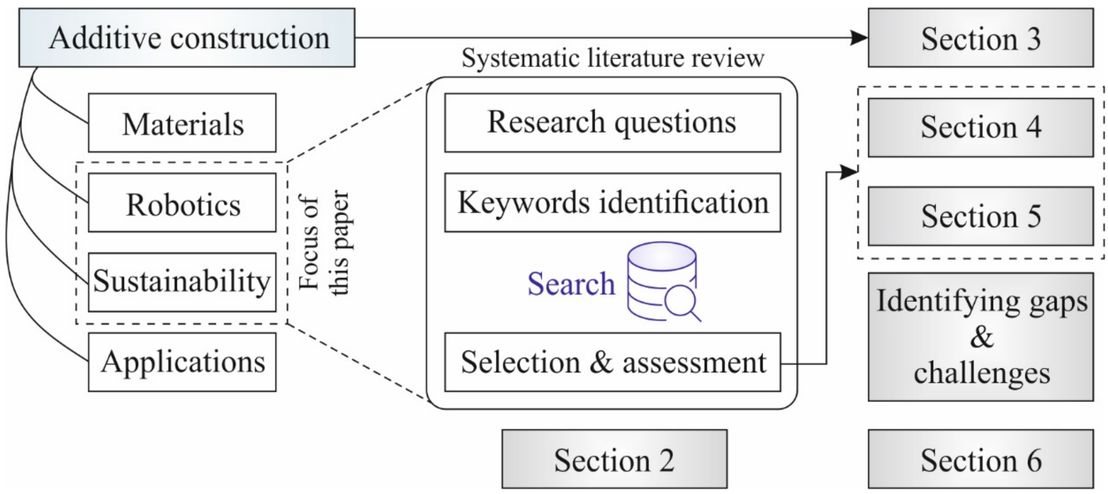

Figure 2. Paper's structure and review methodology.

3. Evolution of 3D Printing in Large Scale Construction

Although AM was introduced in 1980s [29], the literature review indicated that one of the first attempts in cement-based 3D printing towards large-scale additive construction was made by J. Pegna [30]. Given that majority of traditional construction formwork and components are made from cement-based material, the terms "cementitious" or "concrete 3D printing" are frequently adopted in the literature to refer to the field of additive construction and are also the focus of this Section for the purpose of introducing the field. Nonetheless, other types of material, including clay, ceramics, wax, foam, polymers, combinations of these, and even metals (as both structural reinforcements and building components, such as window frames), have also been studied by the literature [31–33]. Considering the beneficial impacts of AM in construction industry, its applications *have progressively increased* in this field. In the following subsections, a brief introductory overview of existing methods, applications, and materials of large-scale AM is provided.

3.1. Methods

Utilizing AM in construction has provided numerous benefits. For instance, it has led to a significant reduction in worker injuries as it is less dependent on a human workforce. Moreover, due to the time-saving and capability of AM in fabrication of geometrically complex components, it is a cost-effective technique [34]. It is noteworthy that, some AM technologies and robotic platforms have the potential to be used in the construction industry under different weather conditions, which can potentially reduce the negative effects of weather on traditional construction [35]. Nonetheless, controlling the print quality remains a critical aspect in such scenarios.

Currently, there are different methods of cementitious or concrete 3D printing in the construction industry, as summarized in Table 1. The main criteria used for each category are the adopted AM technology, resolution of printed features, scale of the components, and the fabrication site. Brief details of these methods are listed below:

- *Contour crafting*: an extrusion-based technique suitable for the construction of a building in a short time [41]. In this method, a gantry system is installed at the construction site to carry the nozzle. The first layer is created by the nozzle movement and after curing it is hard to support the next fresh layer of cement [42]. In Figure 3 several advantages of contour crafting are presented.
- Concrete printing: in this method, cement-based parts are produced layer-by-layer without using trowels. Hence, the resolution of the final structural elements is lower than that of the contour crafting technique. However, in concrete printing, a better control of dimensions is achievable [43].
- *Concrete on-site printing*: developed at the TU Dresden, Germany, and intended to bring 3D concrete printing directly into the building sites. High geometrical flexibility and the utilization of commonly used construction machinery are advantages of this technique [44].
- *D-shape printing*: a powder-based printing method that is suitable for the offsite construction of small-scale structural components [45]. In this technique, the component is built up by bonding of the powder and a binder. In this respect, a printing head with several nozzles must be used to spread the solid powder and the binder. Figure 4 shows a six meter side D-shape 3D printer and print heads.
- *Emerging object*: uses the powder-based technique to selectively harden a proprietary cement composite formulation by the deposition of a binding agent [46]. This technology was developed in the USA and used to manufacture a tall freestanding tempietto with a footprint composed of 840 customized 3D-printed blocks [47].
- It is noteworthy that additional supports are required for concrete printing and the D-shape technique, which consequently increases the production time and waste material. In this case, additional deposition equipment must be used, which can be considered a drawback of these two methods [22]. In addition to the above, the limited printing dimension and low process speed for concrete printing and the D-shape technique, respectively, are among some of disadvantages of these techniques.

3.2. Applications

Among the different applications of AM in large-scale construction are the fabrication of small- and large-scale building components or structures (both on-site and off-site), the printing of acoustic structures, and precast components. In the structures fabricated based on D-shape printing, heat treatment as post-processing can improve durability and the strength of the parts [48]. In Figure 5 some examples of 3D-printed components based on three of the mentioned printing techniques in Table 1, as well as a printed digital grotesque, are illustrated.

Table 1. Cement-based AM technologies for large-scale construction.

Techniques	Advantages	Country	Ref.
Contour crafting	Superior surface finish	USA	[36]
Concrete printing	Smaller resolution of deposition	UK	[37]
Concrete on-site printing	Lower dependency on skilled workers	Germany	[38]
D-shape printing	Construction of complex geometries	Italy	[39]
Emerging object	Construction of interior structures	USA	[40]

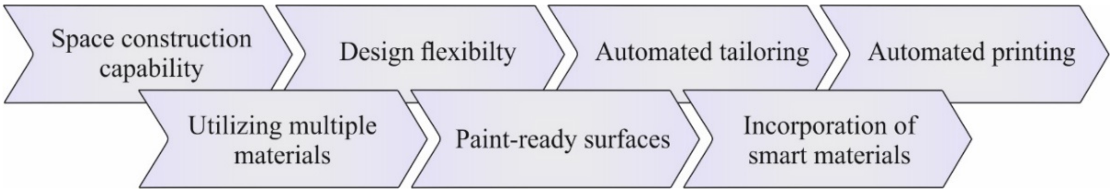

Figure 3. Main advantages of contour crafting.

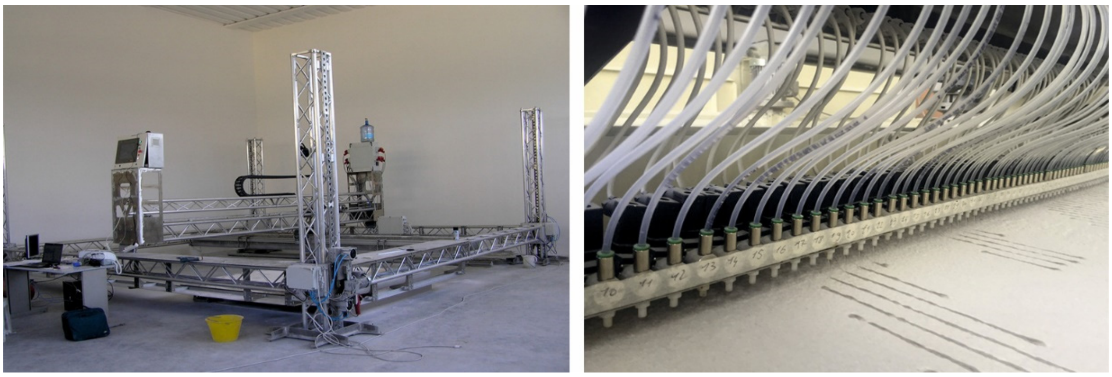

Figure 4. D-shape 3D printer with 300 nozzles (**left**), and print head (**right**) [48,49].

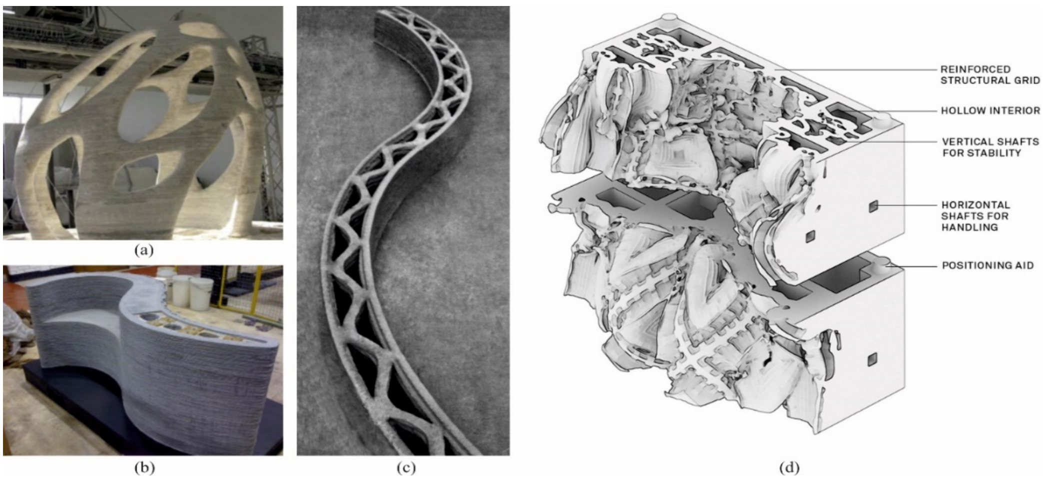

Figure 5. Full-scale printed structures through (**a**) D-shape printing, (**b**) concrete printing, (**c**) contour crafting process [43], and (**d**) printed digital grotesque [48].

Cost reduction is one of the advantages of AM in construction compared with traditional construction. AM is a construction technology that does not use a conventional formwork, while in traditional construction, the formwork represents 35–60% of the overall cost of the concrete structure. Moreover, using AM in construction can reduce the quantity of the workforce associated with development. Consequently, there is a reduction in the cost of servicing staff, for instance, in transportation, cooking, and protection. Although waste materials can be used in AM for construction and it reduces the cost, doing post-processing is unavoidable in some cases, which increases the cost of 3D-printed structures. As AM has been receiving great attention in recent years, further investigation is required to determine the cons and benefits of AM in the construction and building industry.

The qualities and structural performance of 3D-printed parts depend on several factors, such as resolution, printing trajectory, nozzle geometry, printing speed, and post-processing [50]. In many cases, the optimization of these parameters can increase the printing quality [51]. Additionally, there are several parameters that should be determined and defined prior to printing [52], for example, pump pressure, support material, and dimensional parameters (e.g., maximum bead layers) for different printing regions. A comparison of printing techniques shows that the powder-based AM method has significant advantages. More specifically, the powder-based AM method has been considered without limitation in the design phase of structural components. Furthermore, in powder-based AM, structural complexity has almost no effect on the production time. Currently, attempts are being made to answer demands and overcome size limitations in all the AM techniques.

3.3. Material

Based on the several favorable characteristics of cement (e.g., superior mechanical and chemical properties), it is the most used initial component in the construction industry, and consequently among the most popular materials in additive construction. Conventional concrete is easily and readily prepared using cement and some additives, but it cannot be directly utilized in AM applications. In order to use the material for printing purposes, a sufficient yield stress is necessary. Indeed, the material must be able to hold the next deposited layers on the previous layer without deformation. In [53], the properties of 3D printable cementitious materials are explained. There are several specifications that must be met to confirm the usability of concrete in AM. For example, extrudability, pumpability, and level of reliability must be considered and checked before practical applications. In [54], the properties of 3D printable cementitious materials are described. Low viscosity behavior and high yield strength can be obtained by printable materials with thixotropic properties. This type of material can be smoothly extruded, and the final shape of the printed part can be retained after extrusion [55].

Parallel to the advances in printing technology, attempts have been made to improve the mechanical properties of cement-based 3D printing materials. In this context, fiber reinforcements have been performed and different materials, such as polymers, glass, steel, and carbon fibers, have been used [56–58]. In a study by Kosson et al., carbon nanofibers have been used in the fabrication of 3D-printed cement composites [59]. Other experimental [60] and numerical finite element modelling approaches [61] for evaluating different reinforcement strategies, e.g., a concrete beam reinforced with a 3D-printed, bioinspired primitive scaffold, and for predicting of structural failures under various stress cycles have been reported recently. A review of these reinforcement strategies and technologies for the 3D printing of concrete is presented in [62]. Figure 6 illustrates some of the different active and passive reinforcement methods in large-scale AM. In conventional methods of concrete reinforcement, rebar is used, but in AM, special fibers are required which should be sufficiently small in diameter.

(a) (b) (c) (d)

Figure 6. Different reinforcement methods for 3D-printed concrete (**a**) AM via introducing a steel cable into the concrete layer [63], (**b**) early version of reinforcement entrainment device [64], (**c**) contour crafting combined with vertical steel reinforcement [65], and (**d**) reinforcement in contour crafting [66].

Among the adopted material, ordinary Portland cement was used in most of conducted research projects [67–69]. In a few studies, non-Portland binders (e.g., calcium aluminum cements, sulfur-based cement, and limestone calcined clay cements) were used [70–72]. Several recent studies focused on the improvement of material properties and buildability of 3D-printed concrete [73–75]. For example, two technologies for improving buildability in concrete 3D printing were reviewed and discussed in [76]. In the first method, buildability is enhanced during the initial mixing of concrete, while the second technique can improve the buildability at the print-head. The latter includes mixing accelerators, heating, and magnetorheological control at the print-head to increase the yield strength of the material. Moreover, the effects of AM parameters, such as nozzle height and head speed, have been investigated in previous studies [77–79]. For instance, in [80] it was documented that the increase in printing time gap had led to a decrease in bond strength.

Although hybrid printing systems have been used to reinforce 3D-printed concrete and improve mechanical properties, a review of research progress indicated that the development of green construction materials is necessary to decrease energy consumption and minimize environmental impacts. These materials must present suitable flowability, buildability, and extrudability to meet AM requirements. Advances in cement-based printing materials are one of the essential pillars tied to the application of AM in the construction industry.

4. Application of Robots in Large-Scale Additive Construction

Industrial robots are important components of today's manufacturing systems and have been adopted in a wide variety of applications, including manufacturing [81,82], inspection [83], assembly [84], recycling [85], and material handling [86]. An emerging trend in the smart manufacturing of the future is robotic AM [87–89], which introduces numerous advantages in the fast, efficient, and sustainable printing of high-quality customized products. More specifically, in the field of automated construction and large-scale AM, robots have found to be key enablers and extremely beneficial as they are reliable and versatile, thus enabling multiple tasks or processes at the same time by adjusting the end effector [90].

Figure 7 summarizes the different aspects, using which the current studies and developed robotic solutions for automated additive construction in the literature can be classified, with the "platform" as the most commonly used category of classification. However, when it comes to the unique aspects of such robotic solutions, consideration of the locomotion and teamwork methodologies in addition to the adopted platform should be explored. Consequently, in the following subsections, we explored these three aspects individually. Moreover, given their lower significance, fewer available studies, and their connection, the aspects of process, application site, application, and material of robotic solutions are explored jointly in one subsection. The robotic solution is found to be suitable to print components of different sections, such as the foundation, the walls, and the roof. Moreover, the print materials and parameters can be adjusted/changed from one section to another to address their requirements. For example, one may decide to integrate the hollow section inside the walls to accommodate for the installation of insulation, cables/wires, and pipes. In that case, the infill pattern and path plan are adjusted to create the required hollow structures. Moreover, the fabrication site of those sections (on-site/off-site), material, and the height and size of the components could also guide one in identifying the proper robotic solutions, such as the type of the robotic solution (e.g., gantry versus articulated) and mobility.

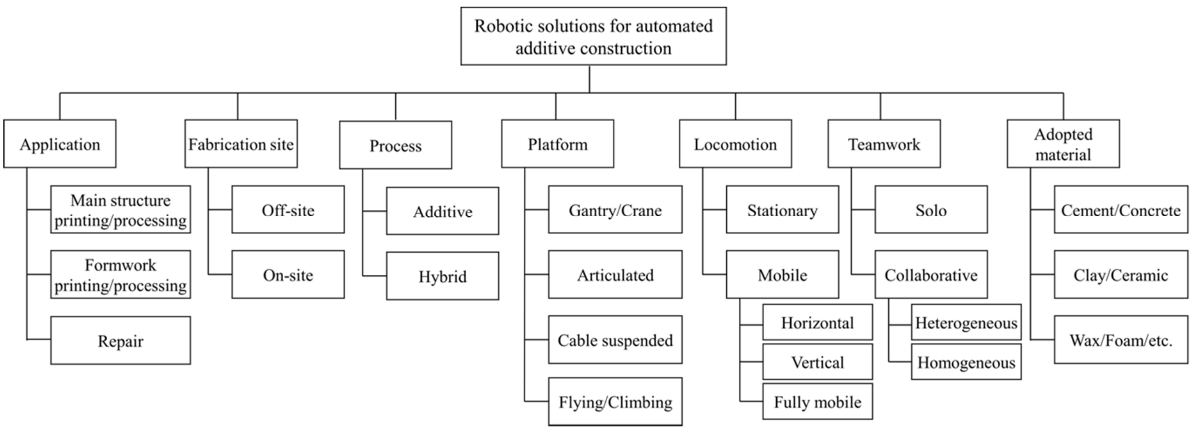

Figure 7. Categories and different aspects of the adopted robotic solutions for automated additive construction.

4.1. Platform

The adopted robotic platforms for automated additive construction include gantry/crane robots, articulated robots, cable-suspended robots, and more recently proposed flying and climbing robots.

Gantry and crane robots: Traditionally, gantry and crane robots have been adopted in industrial settings for a large number of tasks due to their stability and ability to handle high workloads [91]. Consequently, the majority of existing large-scale AM platforms reported in the literature are based on stationary gantry or crane systems/robots equipped with an extruder and material feeding system. Gantry-based 3D printers are equipped with actuators that control the linear movements along the X, Y, and Z directions of the cartesian coordinate. Cranes or one-legged gantry robots, on the other hand, are capable of rotational movements in addition to the vertical and horizontal movements. Nonetheless, both robotic systems can only print structures that are encompassed within their build envelope. Examples of these additive construction platforms include gantry-based contour crafting [92], D-shape or selective binding processes [48,49], and concrete printing [50,93]. Figure 8 illustrates crane and gantry robots and their application in large-scale AM.

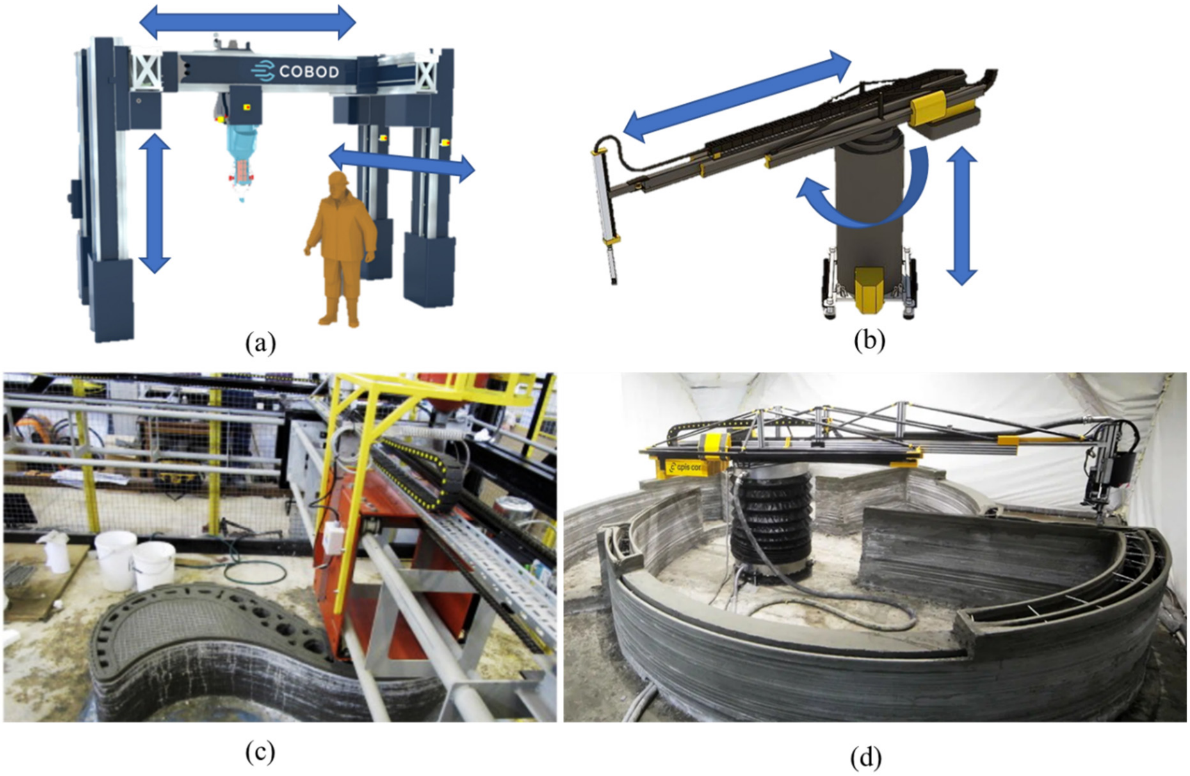

Figure 8. Gantry and crane robots for large-scale AM (**a**) illustration of a gantry robot printer and its three axes—COBOD [94,95], (**b**) illustration of a crane robot printer and its three axes—ApisCor [96], (**c**) concrete printing using a gantry robot [37], and (**d**) concrete printing using an ApisCor crane robot [94,96].

Although the programming, planning, and control of these robotic solutions towards automated sustainable construction are challenging tasks [97–99], they are still considered relatively easy when compared to other types of robotic platforms, such as articulated, cable-suspended, flying, or collaborative printer robots. However, the limited reachability and degrees of freedom (DOF) of gantry or crane robots (i.e., generally three) limits the direction of build and types of structures they can fabricate. In order to ensure the quality of print, and minimize the risk of collision, recent studies has focused on the integration of smart sensors and vision systems to the gantry or crane robot solutions for real-time monitoring and control [100].

Articulated robots: Another popular robotic platform for additive construction is based on articulated robots. In most cases, commercial robots are adopted due to their availability and pervasive technology advances, and AM end effectors are designed and mounted on the robot arm. The application of robotic arms for AM instead of overhead crane or gantry systems has received significant attention in the past few years [101,102]. For example, a large-scale printer robot arm for the fabrication of ultra-high performance concrete was developed in [103] based on a novel tangential continuity slicing method. Kwon et al. [104] later developed a stationary articulated 3D printer robot for the mold-less fabrication of carbon fiber-reinforced thermoplastics. Chan et al. [105] adopted a stationary robotic arm for AM based on the direct ink writing process and investigated the effect of the solids volume fraction of an aqueous clay paste suspension on its printability. Virdis3D [102] is a stationary particle-bed 3D printing robotic platform with an accuracy of 0.01 inch and capable of fabricating sand molds, mold cores, and investment casting patterns. Powder-based robotic printers are generally less studied or addressed compared to extrusion-based robotic printers due to the more complex nature of the process, higher maintenance requirements, and higher volatile organic compound emission potentials.

Cable-suspended robots: Cable-suspended robots are among the less expensive and more transportable solutions towards large-scale AM [106] compared to the previous approaches, but have a few drawbacks with respect to control and accuracy [107], especially under extreme weather conditions, which are less explored [108]. These parallel robotic solutions generally consist of an end effector attached to an external frame using multiple cables. The end effector is manipulated by retracting/extending the attached cables using a set of motors. Additionally, the frame can be easily reconfigured, disassembled, and reassembled to modify the workspace. One of the first cable-suspended robots proposed for automated large construction and AM is based on RoboCrane [109], a crane-type robotic platform proposed by a group of researchers at NIST. Bosscher et al. [106] proposed a fully automated cable-suspended robotic solution called Contour-Crafting-Cartesian-Cable (C4), a robot for contour crafting. Barnett and Gosselin [107] introduced a six DOF cable-suspended parallel robot with unique features, including geometric feedback and support techniques with promising potentials for large-scale AM. Izard et al. [110] further showcased the limited collisions from the cables of these platforms for large-scale AM applications. To enable large-scale fabrication, a novel system design was recently proposed by Jung [111] which could minimize cable inference while maximizing the workspace. One of the tallest commercial parallel robotic solutions has been developed by WASP, a 3D printing company based in Italy [112]. Their "BigDelta WASP 12m" model, shown in Figure 9b, is a 12 m high and 7 m wide printer with a payload of 200 kg, and has been frequently adopted in the field of low-cost sustainable housing construction. SkyBAAM [113] is another cable-driven robotic platform for large-scale fabrication developed by the Oak Ridge National Laboratory (ORNL) and studied in detail with respect to its kinematics [114]. Although cable-driven 3D printers are promising in the field of construction, future research in the areas of vibration reduction, the accurate control of cable motions especially in outdoor environments, the integration of online vision systems for real-time quality control, and system design improvements to simplify the vertical motions for printing tall structures are required.

(a) (b)

Figure 9. Cable-driven large-scale 3D printers (**a**) Cogiro cable-driven parallel robot with a Pylos extruder [110] and (**b**) BigDelta WASP [112].

Flying robots: Drone technology or unmanned aerial vehicles (UAVs) are frequently adopted for surveillance of construction or mining sites, collecting asset data, monitoring construction progress, inspection, and even assembly/construction by picking and placing material [115–119]. Nonetheless, combining AM with flying robots for construction purposes is far less explored. The aerial maneuver capability makes 3D printing flying robots extremely beneficial for the in situ repair of large-scale structures, such as bridges, or for accessing areas that are generally inaccessible by the robotic solutions (particularly ground-based robots) discussed above. Hunt et al. [120] were among the first group of researchers to develop a 3D-printed flying robot prototype for midflight printing and demonstrated its potential for repairing damaged structures and bridging gaps in terrains. Dams et al. [121] further demonstrated the feasibility of aerial 3D printing, using drone technology for repairing civil engineering structures using expanding polyurethane foam. To realize large-scale additive construction using flying robots, several challenges need to be addressed with respect to the limited suitable material availability, low payload capacity, stability issues affecting print accuracies, short battery life of existing flying robots, as well as limited efficient material delivery and refill solutions between print cycles. In addition, due to the small size of the available flying robots and the relatively slower print speed, the fabrication of large structures would probably be ideal only if a team of flying robots are assigned to the task. Consequently, the majority of existing research on 3D printing with flying robots is limited to repair applications and proof of concepts.

Climbing robots: More recently, the idea of climbing 3D printing robots to address the printing size limitations was explored. Koala 3D [122] is among the first continuous climbing 3D printers that can navigate vertically along an object being fabricated, thus producing objects that are larger than itself. Although the authors only printed small-scale structures using the developed climbing robot, the potentials of this approach for large-scale construction were discussed and highlighted. Climbing robots, similar to flying robots, are expected to have more flexibility and less limitations with respect to the maximum size of the structures they can fabricate when compared to other terrestrial mobile printing robotic solutions. Moreover, they are expected to be more stable compared to flying robots because of their anchoring capability. However, as this is an emerging concept especially in the field of large-scale fabrication, a significant amount of research is still required to address the following challenges: (i) the effect of robot weight, the anchoring mechanism, and anchoring points on the deformation of printed objects, especially in cement-based material; (ii) the multi-stage recalibration requirements after re-anchoring stages to increase accuracy and precision; (iii) the existing print speed limitations; and (iv) feasible path-planning strategies and climbing mechanisms for complex objects.

4.2. Locomotion

The existing robotic solutions for additive construction can be categorized into mobile and stationary based on their locomotion properties. Stationary robots are grounded robots which can only operate within their build/reach envelope. Mobile robots, on the other hand, can reposition themselves (during or in between processes) in order to reach different locations or regions and expand their working volume. Mobile robotic solutions generally require a more advanced vision and control system for navigation, localization, and relocation [123] to eliminate collision, reduce print inaccuracies, and address fine tolerances. In addition, while relocation during the process (i.e., printing while repositioning) can provide much larger continuous work volumes compared to relocation in between processes (i.e., printing while stationary but repositioning in between builds), it requires a full body motion planning which is generally more sophisticated and thus less explored in the literature [124,125].

In the context of large-scale additive construction, the majority of the adopted robotic solutions (e.g., gantry or cable-suspended robots) are stationary due to their grounded base and can only print structures that are located within their build envelope. This translates into the large size of these platforms since they should be large enough to fully encompass the construction structure. On the other hand, few studies have explored the application of mobile robots, mainly mobile articulated robots, in large-scale additive construction, as illustrated in Figure 10. A mobile robotic platform named "ATHELET: All-Terrain Hex-Limbed Extra-Terrestrial Explorer" was proposed in [123] for the large-scale AM of walls, hard paving, domes, etc., using materials extracted from the local environment. In [126], a sensor- and camera-equipped holonomic mobile platform with ArUco markers was adopted for the localization, odometry, and repositioning of the robot arm during the printing process. The digital construction platform (DCP) proposed in [124] is a material- and process-independent platform based on a mobile compound robotic arm system with a radial reach of over 10 m and load capacity of 158 kg. The platform is composed of a large mobile aerial lift system (Altec AT40GW), a smaller six DOF electric robotic arm (KUKA AGILUS KR 10 R1100 sixx WP) mounted at the aerial lift's endpoint, and a laser sensor, mounted on the KUKA wrist, for environment sensing, platform control, and repositioning. So far, the motion planning and control of these mobile compound robotic platforms and the closed-loop control for high accuracy printing based on advanced image processing and machine learning techniques remain as the most critical challenges in this field [127,128]. Moreover, multi-axis tool path planning and topology optimization are among the other directions of research [129,130].

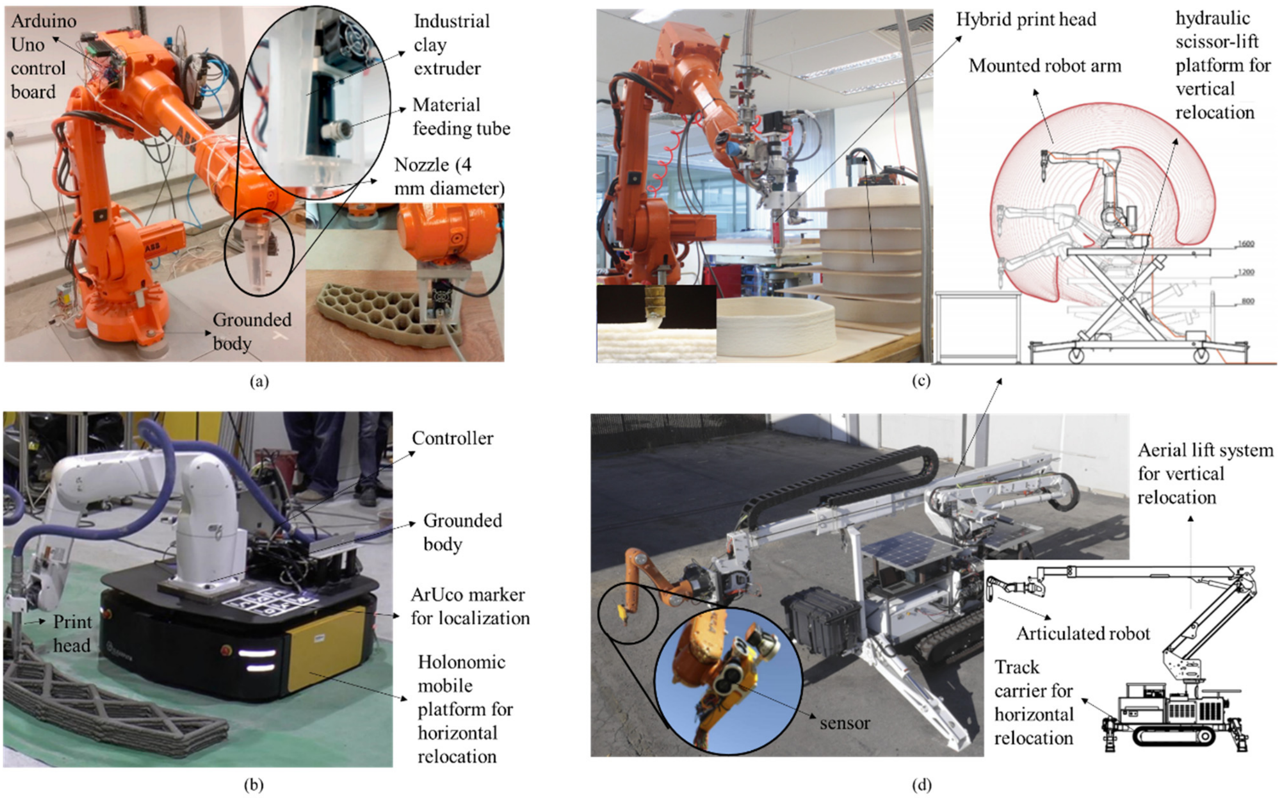

Figure 10. Different categories of articulated robots for large-scale AM (**a**) stationary articulated robots [131], (**b**) horizontally mobile articulated robots [126], (**c**) vertically mobile articulated robots [132], and (**d**) both horizontally and vertically mobile articulated robots [124].

While mobile articulated robotic arms can expand their working and reach envelop, their vertical reach is still limited as their mobile platform (either a wheeled carrier, aerial lift, or holonic platform) is still considered to be grounded. In addition, ground mobility can be easily compromised in rough terrains or routes. Consequently, mobile robotic solutions that can access the targets using an aerial path, such as drones/UAVs, have become popular.

4.3. Teamwork

One of the rather more effective and economical solutions for AM of large-scale components in a short amount of time is using a team of robots, also commonly referred to as swarm robotics or collaborative robots, instead of a single robot. The vision to adopt an "army of mechanical ants" in the field of large-scale additive construction, was first introduced by Pegna in 1997 [30]. In this approach, multiple coordinated (generally mobile) robotic agents work together efficiently to perform the assigned task, i.e., printing the structure in our case. However, optimal coordination and planning among such systems towards higher efficiency and print accuracy/quality remain open challenges in the literature. Traditionally heterogeneous and homogeneous swarm robotics (Figure 11) have shown promising potentials in many construction and non-construction applications [133], including assembly and bricklaying [134–136] and continuous fiber or filament winding [137–139], as well as hazardous or extra-terrestrial environments. In the field of additive construction, however, multi-robot systems are rarely studied in the literature.

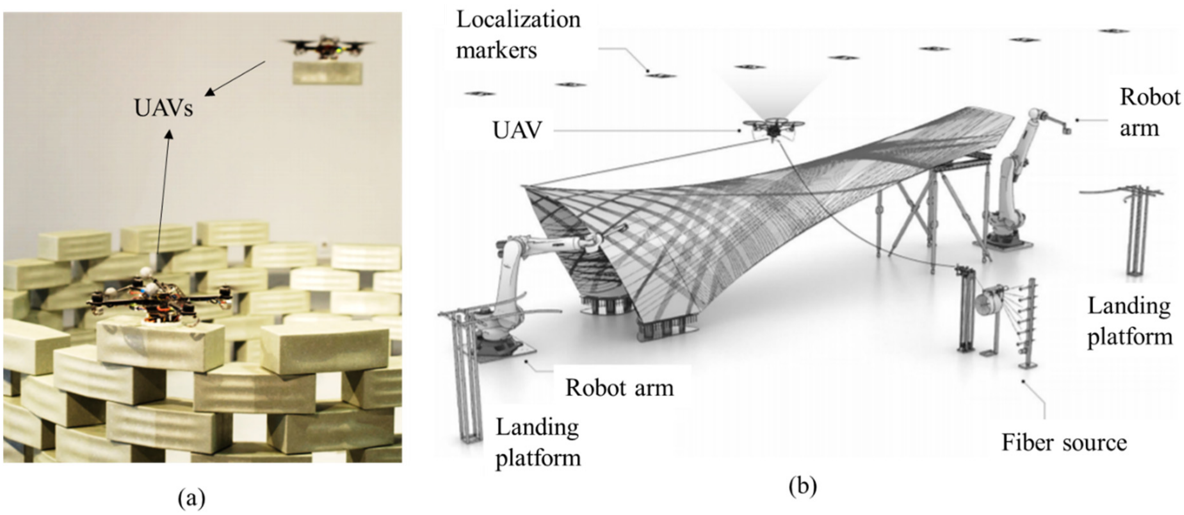

Figure 11. Illustrations of different categories of multi-robot solutions for non-AM based construction (**a**) homogenous, i.e., uniform entities [135], and (**b**) heterogeneous, i.e., diverse entities [139].

The feasibility of large-scale AM using a team of ground-based mobile robots was recently explored by Zhang et al. [126] and Shen et al. [140]. In [126], each entity consisted of an articulated robot arm mounted on a holonic mobile platform, as shown in Figure 12b, which could move around the component. In addition, the different modules for optimal segmentation, robot positioning, motion and trajectory planning, navigation, localization, task assignment, and deposition were discussed. On the other hand, Shen et al. [140] adopted a parallel positioning of stationary articulated robots located on opposite sides of the geometry, as shown in Figure 12a, enabling the continuous extension of the platform from the sides. Both studies observed superior efficiency of their multi-robot platforms for additive construction when compared to single-robotic solutions. Sustarevas et al. [141] developed a mobile robotic printer called "YouWasp" and explored different methods and algorithms towards task decomposition, allocation, and collision-free printing between a team of autonomous printing entities using both simulation and physical experiments. In addition, they investigated the accuracy of the print and highlighted the necessity of a multi-scale sensing and layered control system for a higher accuracy of the print structure. The segmentation and scheduling tasks of multi-robot cooperative 3D printers were also addressed by Poudel et al. [142,143] for collision-free 3D printing. The potentials of adopting multiple robots/drones for assembling droxels, a novel 3D-printed block-based construction structure, was also recently proposed and experimentally studied via a ground-based articulated arm [144].

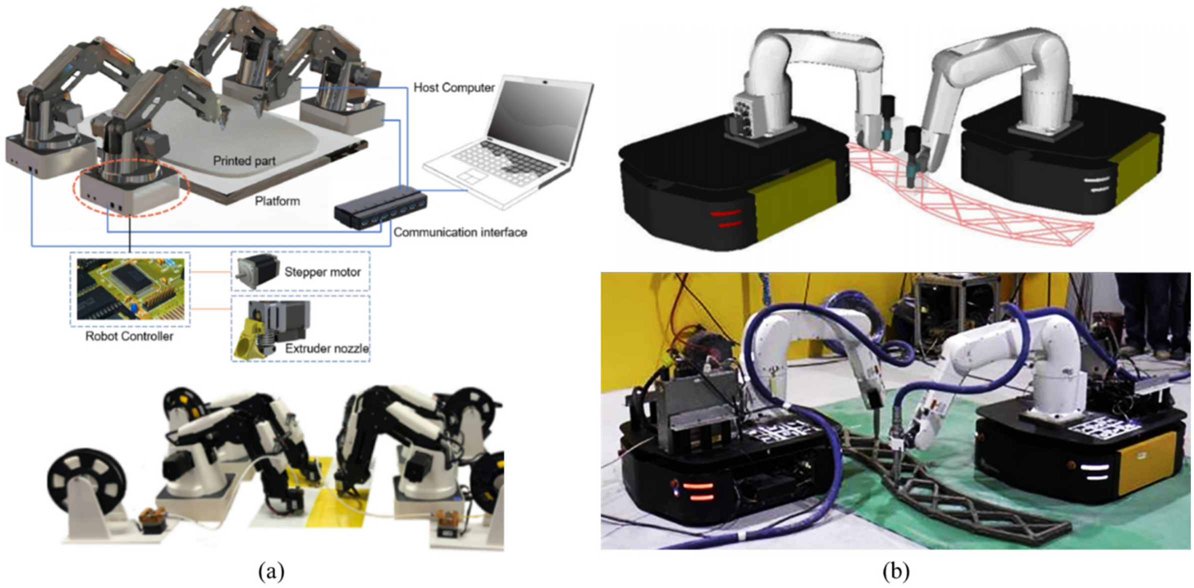

Figure 12. Developed multi-robot 3D printing system by (**a**) Shen et al. [140] with stationary robots, and (**b**) Zhang et al. [126] with mobile robots.

4.4. Application, Fabrication Site, Process, and Material

Application and fabrication site: The different application domains of robotic solutions for additive construction can be summarized as follows: on-site fabrication of the main large-scale structures [41,92], off-site prefabrication of full-scale components for construction of buildings, including panel and walls [145–147], fabrication of formwork [148–150], and repair of construction structures [120]. The fabrication site and application aspects are generally tied to the adopted robotic solution, including the platform, locomotion, and teamwork capability. As an example, although crane/gantry or cable-suspended robots might be a more suitable option for the on-site fabrication of buildings when compared to an articulated robot, a team of collaborative articulated and flying robots with mobility might be considered an acceptable replacement strategy depending on the maturity of existing technologies, case-specific requirements, and budget constraints. On the other hand, a flying robot would be a more cost-effective option for the repair of infrastructures compared to a gantry. In other words, gantry/cranes and cable-suspended printer robots are currently the most cost effective in the factory setting for the off-site pre-fabrication of large construction components, and their adoption for the on-site fabrication of full-scale buildings is limited due to their economic concerns, their limitations to printing structures larger than themselves, inefficiency to print overhangs and some other complex features, and instability under extreme weather conditions.

Process: In addition to the printing of large-scale structures using various AM technologies, the adoption of robotic solutions for the surface finishing of large-scale structures or surfaces, in form of a hybrid process, have been explored in a few studies. As an example, the FreeFAB process [148], is a gantry-based robotic system for coarse 3D printing and the subsequent milling of complex formwork and molds up to 30 m $\times$ 4 m $\times$ 1.5 m in dimension. The hybrid additive and subtractive manufacturing capabilities led to significant cost and time savings compared with traditional approaches. For example, in an attempt to reduce the need for surface finishing or post-processing, Lim et al. [151] demonstrated the feasibility of curved-layered concrete printing for the fabrication of large-scale construction components with smooth surfaces. It is noteworthy to mention that although studies on hybrid AM techniques are abundant in the literature [152–154], their applications for large-scale additive construction and their challenges are rarely explored. Thus, further investigation is needed to shed light on the practical problems in this field.

Material: With respect to the material research tied to the robotic solutions, the development of lightweight reinforced material with high durability and possibly expansion capabilities for the repair of construction structures is necessary given the low payload capacity of existing flying robots, as also highlighted in the literature [121].

5. Environmental Impacts and Sustainability of Additive Construction

Based on the literature, the existing studies on environmental impacts and sustainability of large-scale additive construction can be classified into three distinct categories: (i) sustainability of the process, (ii) sustainability of the material, and (iii) sustainability of the printed structures. The following subsections summarize the ongoing research within each of these categories.

5.1. Environmental Impacts of the Additive Construction Process and Adopted Robotic Solutions

Due to the proliferation of AM in a wide range of applications as well as increasing environmental concerns, AM's environmental impacts and sustainability have become an important issue in the community [155]. Although additive construction is generally reported as an environmentally friendly alternative to traditional construction techniques [156], detailed research on different aspects, such as energy consumption, waste materials, and air pollution of the additive construction process and the adopted robotic solutions, should be considered. The LCA method is among the most popular approaches in the literature to evaluate and compare the environmental impacts of the additive construction. For example, Agustí-Juan et al. [157] compared the sustainability of robotic additive construction with the conventional construction method through the life cycle assessment (LCA) method according to ISO 14040-44:2006 [158]. In this regard, several factors, such as human toxicity, freshwater eutrophication, freshwater ecotoxicity, water depletion, and metal depletion, were considered. Another recent study used the LCA method to study and compare the environmental sustainability of a hybrid additive–subtractive concrete printing process based on a cable-suspended robot with traditional injection molding process [159]. It was observed that in mass production scenarios, both the hybrid and conventional approaches have similar environmental impacts due to the potential re-use of the mold. More recently, Batikha et al. presented a comparative study and reported that 3D concrete printing behaves similar to cold-form steel and produces approximately 32% less CO2 emissions compared to other construction techniques [160]. Table 2 presents the most recent studies that used LCA to determine environmental effects of AM for concrete construction.

Table 2. Utilized LCA for evaluation of AM in concrete construction.

Material	AM Process	Main Environmental Effects Contributor			Ref.
Concrete	Extrusion-based	Concrete	Printing system	-	[161]
Concrete	Extrusion-based	Concrete	Electricity	Formwork	[162]
Cementitious	Extrusion-based	Electricity	Carbon emission	-	[163]
Concrete	Extrusion-based	Concrete	Electricity	Transportation	[164]

More recently, analytical efforts towards characterizing and minimizing the environmental impacts in additive construction have been reported. For instance, Haghighi et al. [165] proposed a framework for energy-efficient multi-robotic AM in large-scale construction based on a team of articulated robot arms equipped with automated guided vehicles for horizontal motion and relocation. The concept of the reciprocal energy map was adopted for the optimal positioning and relocation of printer robots to minimize the energy consumption.

The environmental benefits of AM are more visible in the construction of complex structures. Indeed, geometrically complex structures can be constructed without significant additional environmental impacts, as also reported in [157]. Therefore, the benefits of AM in construction industry increase proportionally based on the complexity of the structural elements. In contrast, in conventional construction techniques, higher complexity generally leads to more waste materials. As AM is energy-intensive, the application of renewable energy sources in the 3D printing of concrete can make this process more sustainable economically and environmentally. Moreover, the environmental prospective of AM in the construction industry depends on other factors, such as greenhouse gas emissions, energy generation, and transportation methods, hence, further research is required to determine the effects of these factors in detail.

5.2. Sustainability of Materials for Large-Scale AM

The mechanical performance of a 3D-printed structural component depends on a mix of design (e.g., cement type, water to cement ratio), printing parameters (e.g., printing speed, extrusion pressure), and external environmental conditions. Therefore, the type of material has a significant effect on the sustainability of the final product, and optimized parameter values are required to obtain sustainable 3D-printed parts. In [89], it has been documented that AM has a great potential for the reduction in material usage in the construction industry. This is achievable through the construction of complex geometries without supporting materials based on topology optimization. Large-scale AM generates less material wastes compared to traditional techniques and raw materials with low embodied energy must be used for optimization purpose. In [166], two types of construction material in large-scale AM were compared. To this aim, LCA was used to study concrete and cob (a sustainable earth-based material). The evaluation indicated that cob-based construction followed by AM leads to lower environmental impacts. A series of recent studies has investigated 3D-printed materials in the construction industry [167,168]. For instance, in [167] a feasibility study was performed on sustainability of magnesium potassium phosphate cement paste for 3D printing. In this respect, researchers used magnesium potassium phosphate cement with different ratios of fly ash and evaluated the different properties (e.g., buildability, porosity, and compressive strength) of the 3D-printed samples. It was concluded that using waste cementitious materials increased sustainability. There are several studies which considered earth-based materials (e.g., cob) as sustainable construction materials for large-scale AM [169–171]. Cob consists of sand, clay-rich soil, water, and straw and exhibits high indoor air quality and sustainability benefits.

Over the past few years, there has been a significant increase in the amount of research on the use of geological and recycled materials in large-scale AM. For instance, the AM of geo-polymer concrete for sustainably built environments has been investigated in [172–174]. The AM of geopolymer as a promising technology was introduced in [172]. Indeed, application of fly ash based geopolymer cement for 3D printing of structural elements was evaluated. Based on the experimental results, it was reported that the mechanical properties of 3D-printed geopolymer are dependent on the loading direction, and this material can be used as green material. Sustainable cement-based composites have been examined in [175]. In fact, a cement-based composite containing microcrystalline cellulose was developed and tested. Experimental practices confirmed that microcrystalline cellulose improved the rheological properties and increased yield stress significantly. The microcrystalline cellulose is considered sustainable, because of its renewability and biodegradability. Later, in [174] the life cycle of geopolymer concrete was investigated. Although utilizing 3D printing geopolymer concrete can reduce the carbon footprint, it has a negative influence on abiotic resources. Researchers found that a reduction in silica in the recipe of the geopolymer can improve sustainability and environmental benefits. A study by Bhattacherjee et al. [176] explores the sustainability aspects of binders used in concrete 3D printing. To this aim, the literature on the different binder systems used for producing 3D printable mixtures is reviewed. In fact, the researchers emphasized the influence of using supplementary cementing materials for improving the sustainability of 3D-printed structures.

Currently, material waste is one of the main problematic issues in the construction industry and recycling is as an effective solution. In [177], Dey et al. presented a review of 3D-printed concrete made with industrial wastes. Utilizing recycled materials in large-scale

AM can solve different problems, which has been investigated in previous studies [178–182]. For example, in [180], waste material was used in mortar–polymer laminar composite. Fly ash was added to normal mortar and a series of compression tests were conducted on the 3D-printed lattice-like sheet specimens. A comparison of the results indicated that specimens containing recycled material offer a lower cost and higher sustainability. At the same time, a solid waste was utilized in 3D printable concrete [181]. In short, different types of municipal solid waste were used in concrete mixtures, and different mechanical tests were carried out to determine the properties of printed parts. The obtained results showed that yield stress was enhanced by utilizing waste materials. Moreover, it was reported that added waste materials have a favorable influence on the rheology of printing concrete. A recent study investigated magnesium oxide (MgO)-activated slag as a cementless material for sustainable AM [183]. Indeed, MgO as an alternative to slag was used for spray-based AM. Based on a series of experimental practices, the dynamic and static yield stresses were determined. Considering the results, it was claimed that the developed mixture can be used as a sustainable material for AM in the construction industry. Recently, researchers quantified the sustainability potential of recycled concrete in 3D-printed buildings [184]. More specifically, key sustainability aspects were identified, and it was reported that the increase in utilizing recycled aggregate has led to less pollutant emissions. In [185], researchers developed eco-friendly mixtures with a high environmental sustainability while retaining the mechanical performance. In particular, three printable eco-friendly mixtures were prepared in which 60% of the cement was replaced with silica fume and fly ash. In recent studies [186,187], recycled glass and aggregate micro fines were used in 3D-printed concrete, respectively. Experiments indicated that the addition of glass particles increased the flexural strength of the 3D-printed concrete. Moreover, the dosage of aggregate micro fines has an influence on the printability of the mixtures, and utilizing aggregate micro fines can improve the compressive strength of 3D-printed concrete.

As documented in [188], the construction industry has a crucial role in the environment worldwide (e.g., 40% solid waste generation, 40% energy consumption); therefore, optimization efforts in this industry have led to significant impacts on its environmental effects. Although utilizing robots and high-tech construction equipment leads to an increase of energy consumption, material scientists have showed the effects of material optimization on the environmental impacts of large-scale AM [189]. Indeed, it has led to the improvement of the energy efficiency of the final building and a better environmental performance over the entire service life. It is also noteworthy that the environmental influence of large-scale AM is different from one location to another, according to the source of energy consumption and its pricing. In detail, when electricity generation is based on fossil fuels, the environmental impact is greater. In [190], different mixtures (modified with reactive and inert mineral additives) were designed for AM and examined. Particularly, the mixes were evaluated in terms of their rheological and mechanical properties as well as their environmental impact. The obtained results proved that a suitable material modification of mixes for AM can significantly reduce the negative impact on the environment without hindering the required AM properties.

Since properties of 3D-printed concrete play crucial roles on the performance of printed structures, the testing and evaluation of the properties are important. In this context, different testing measuerements are developed to examine the printability, durability, and mechanical properties of 3D-printed concrete. Although several conventional workability testing measuerements cannot be used for the evaluation of 3D-printed concrete, slump and slump flow can be used to determine a suitable range of printing. Moreover, measuring the properties of components during the printing process is another method to measure the printability of concerte. The peneration test measures the mechanical properties of fresh 3D-printed concrete. In addition, ultrasonic pulse velocity can be used as a non-destructive method to measure the fresh mechanical properties of 3D-printed concrete. The test methods which are currently used for conventional concrete can be utilized by determining the mechanical properties of hardened 3D-printed concrete; however, the specimen preparation could be different.

Although 3D-printed structural elements have been used in different applications, there are no specific documents about the structural performances of these elements under different weather conditions and severe environments. Due to the global growth of 3D printing, the above-mentioned area needs further research and practical investigation.

5.3. Sustainability of Large-Scale 3D-Printed Structures

While analyzing the sustainability of both process and material in large-scale AM is critical, the sustainability of the printed buildings or constructions is equally important. More specifically, with the advances of existing large-scale AM techniques, it is envisioned that many residential or non-residential buildings of the future can be constructed with such technology. Consequently, it is important to evaluate the sustainability and energy efficiency of these structures [191]. Few efforts to compare the sustainability of 3D-printed buildings with conventional techniques during construction are found in the literature. For example, a comprehensive environmental assessment of 3D-printed building elements can be found in [192]. In detail, LCA was applied for two case studies to evaluate the environmental impacts of AM and the traditional construction method. The first case was the "Sequential Roof" which is a wooden roof of Arch Tec Lab. The second case study was the concrete–sandstone composite (CSC) slab prototype, as seen in Figure 13 (both cases from ETH Zurich). The material and fabrication information was collected to evaluate the environmental impacts. The LCA results were divided into different building components: suspended ceiling and structure. Moreover, the analysis presented the global warming potential of building elements.

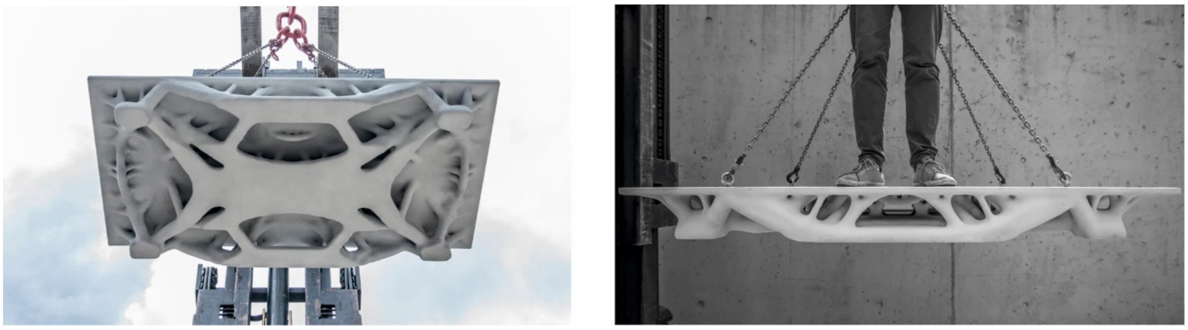

Figure 13. 3D-printed prototype of CSC slab (Digital Building Technologies, ETH Zurich, Switzerland) [193].

According to the results, significant environmental benefits were obtained during production in both case studies. It was concluded that a minimum of 30 years should be taken into account for the service life of the multi-functional building elements in order to provide environmental benefits. Additionally, the investigation indicated that the amount and type of building material play important roles in life-cycle environmental impact. In fact, utilizing recycled materials is very beneficial, but a lack of quality standards can lead to health risks which has a big effect on the demand for recycled materials. Han et al. [184] also used the LCA method to evaluate and compare the pollution as a result of concrete printing and conventional construction for the fabrication of two hypothetical building models. The pollution caused by AM was found to be more severe due to the higher concentration of cement content. Moreover, the increase in the cost of electricity caused by AM was reported to be insignificant when compared to the savings in formwork and labor. In [194], a cradle-to-grave LCA analysis was performed for a comparison of a terraced-type building (with a 60 m^2 floor area and potentially 2–3 occupants) fabricated by AM and conventional construction techniques. The results confirmed the lower environmental impact of 3D-printed buildings.

Another interesting analysis is with respect to the sustainability of 3D-printed buildings at the design and application stages. This would include the assessment of different design strategies, internal printed features, and semi-hollow structures on the thermal insulation of printed structures/buildings and their overall energy efficiency. Mahadevan et al. [195] adopted a simulation-based approach to compare the thermal comfort and building energy efficiency of a simple house using three different materials, including 3D printable concrete, M25 concrete, and conventional brick masonry. It was pointed out that despite the lower environmental impact of AM during the construction stage, the energy costs of 3D-printed buildings in long term as well as the net annual CO_2 emissions are generally higher when compared to conventional constructions with traditional material. Consequently, an additional comprehensive investigation on the entire life cycle of 3D-printed buildings is required. Moreover, the adoption of thermal insulating cement or material [196,197] in 3D printing for increasing the environmental sustainability of buildings can be investigated. In order to investigate the environmental sustainability of 3D-printed buildings, thermal comfort and building energy efficiency should be considered.

He et al. [198] proposed and fabricated a modular building envelope with an integrated vertical greenery system, named the 3D-Printed Vertical Green Wall (3D-VtGW), using concrete 3D printing technology. Additionally, the energy saving potentials of a small commercial building assembled from the proposed green walls were studied considering the weather data of Nanjing, China. Interestingly, it was observed that the combined effect of plant shading, evapotranspiration, and heat storage from soil contributed significantly to the building's energy savings.

Based on increasing demands and current environmental circumstances, adaptation in AM is required as this technology is sustainable for the construction industry. In this respect, further attempts, such as developing an instrument for evaluation of sustainability of 3D-printed building products, are needed.

6. Challenges and Future Prospects

The application of AM in construction of complex structural elements is a relatively new concept and has been confronted with several challenges. Here, we have summarized the main challenges and future prospects of utilizing AM in the construction industry with respect to the existing robotic solutions and environmental sustainability issues.

6.1. Automated Robotic Additive Construction

Design and Hardware: Most of the existing literature is focusing on proof of concepts and the development of various robotic solutions for efficient and controlled 3D printing of structures based on different designs and hardware (robotic solutions, tools, as well as deposition and locomotion mechanism). Although significantly valuable, these studies rarely account for weather conditions and their impact on the ideal design of robotic solutions, as most of the prototypes are either tested in laboratories and off-site closed environments, or under normal weather conditions. As an example, the functionality of cable-suspended robots or flying robots could be easily tested under extreme weather conditions [108]. Moreover, some of the existing robotic designs or mechanisms (e.g., flying robots) are still incapable of efficient controlled printing for large-scale construction due to their hardware limitations (e.g., limited battery life, inability to carry the construction material due to their weight limitations, or inability to print mid-relocation). Therefore, novel robotic prototypes and designs considering the existing challenges need to be developed. Finally, as the economical concern is one of the main focuses in further development, additional efforts are required to propose additive construction solutions with reasonable costs of production and maintenance in the construction industry.

Software and control: In addition to the hardware design and printing mechanism, the establishment of standard control software and protocols towards the efficient printing of large-scale structures with acceptable quality using single or multiple robotic solutions would be necessary. Nonetheless, such computational framework and standardization efforts are rare and thus, would significantly hinder the widespread adoption of robotic solutions in additive construction. It is also expected that due to complexity of the planning tasks in additive construction, machine learning and data analytics solutions would play an important role in establishing such computational frameworks.

Collaborative robotic solutions: multi-robot collaborative robotic solutions (capable of collaborating with other robots as well as construction workforce) are among the emerging topics in the field with many unanswered questions, including the optimum planning, assignment, and scheduling of tasks among the parties considering sustainability, print quality, and safety concerns [126,140]. Studies on multi-robot additive construction are currently rare and mainly limited to the development of such prototypes with less attention given to the above planning challenges. Therefore, establishing an analytical and computational framework for the energy efficient collision-free process planning of such multi-robot additive construction platforms, including optimum part segmentation, task allocation, scheduling, trajectory planning, and relocation, based on the characteristics of the robotic solutions and the adopted AM processes, is necessary. Moreover, despite the existing studies on human–robot collaboration in the general field of manufacturing (e.g., assembly tasks), human–robot collaboration in the field of additive construction (e.g., construction workforce adding metal bar reinforcements mid-printing) and its safety challenges for the efficient and safe collaboration of both parties are currently not addressed in the literature.

Material and material feeding mechanism in mobile robots: in addition to the development of necessary software and control systems, the development of novel material feeding mechanisms for construction scenarios involving mobile robots is critical to minimize print interruption and collision of such material feeding systems with existing construction equipment, workers, and other robots. Moreover, utilizing flying robots for the repair of construction structures is an emerging field with many challenges yet to overcome and few studies available. In these cases, the development of lightweight material with high durability and possibly smart expansion capabilities (e.g., by leveraging the 4D printing material) is necessary, given the low payload capacity of existing prototypes [120].

Quality quantification: The decisions on the adopted robotic solutions and planning/scheduling tasks can impact the quality of the print. Although there are several analytical models and methodologies for quality characterization in different AM techniques and common printing materials, the unique quality challenges in large-scale robotic additive construction are not currently addressed in the literature. As an example, the segmentation of a large-scale structure into smaller pieces, with each assigned to one robot for printing, can create unique quality challenges that do not exist when the whole structure is printed using a single 3D printer. Examples of such quality issues are the quality of print (bonding strength) at the touching boundaries of two individually printed segments or print accuracy issues due to robot relocation and motion. Consequently, there is an urgent need for identifying and quantifying the quality of print and various challenges that can rise as a result of robotic solution-specific decisions and planning using analytical models.

Hybrid robotic solutions: Hybrid manufacturing technologies (those integrating multiple manufacturing processes into one single platform) are traditionally known for their unique capability of leveraging the advantages of all those processes while minimizing their drawbacks. As an example, a hybrid additive–subtractive process has shown potentials in producing complex geometries with a higher achievable print accuracy (compared to an AM process) as a result of the subtractive process. Consequently, in the field of additive construction, the adoption of hybrid robotic solutions, i.e., robotic solutions that can perhaps perform multiple processes in addition to the AM process, can introduce unique benefits.

Extraterrestrial additive construction: because of specific conditions in space, robotic solutions can be considered as a practical method for extraterrestrial additive construction. Therefore, research regarding the design and fabrication of reliable robotic solutions and AM mechanisms for extraterrestrial additive construction under environment-specific challenges (e.g., low or no gravitational force and extremely high or low temperatures) would be necessary. Moreover, the potentials of adopting local materials for the AM process can also be considered.

Workforce training: Given that robotic control and planning is generally a task that requires expertise, and that all construction planning activities and decisions can impact the quality of the final printed large-scale structures, standardization, workforce training, and employing skilled workers would be necessary in the field of additive construction and are among the existing challenges. In order to keep the pace with the increasing growth of this field, the re-training of workers might also be necessary in the future.

Selection guidelines and standards: It is currently not clear which specific robotic platforms, designs, and their associated capabilities are suitable for various applications in the additive construction field. More specifically, it would be of interest to identify the most appropriate robotic solution under different constraints of application, fabrication site, quality, material, process, environmental impacts, and cost.

6.2. Environmental Sustainability in Additive Construction

Analytical modeling: while additive construction is generally reported as an environmentally friendly alternative to traditional construction techniques [156], and there have been research efforts to theoretically formulate and model the environmental impacts under various processing and weather conditions, the adopted robotic solutions are currently lacking in the literature and need to be established in addition to the frequently performed LCA analyses for various large-scale components or materials. More specifically, formulations of the environment and life cycle impacts should take into account the contribution of various system elements, including the construction material, as well as AM process-specific and robot-specific properties. This is however, as mentioned, currently lacking in the literature with majority of the studies focused on either evaluating the environmental impacts of construction material or comparative studies between various materials or construction mechanisms (e.g., additive construction versus traditional construction).

Emerging robotic solutions: The environmental sustainability of collaborative or hybrid robotic solutions in the field of additive construction is not currently addressed in the literature, perhaps due to the fact that these emerging platforms are currently under initial development phases as proof of concepts. Therefore, as these solutions become more mature, efforts towards quantifying their environmental sustainability and establishing systematic process planning and scheduling methodologies for the efficient and sustainable operation of such systems should also emerge [165].

Standardization: To promote the AM technology in the construction field, general standards and protocols addressing the environmental sustainability of the process should be further developed and documented [155]. These standards will guide decision makers in selecting the right material and process mechanism with respect to their applications, considering their impacts on the environment.

Material recycling and local material extraction: Although beneficial to the environment, the potentials and challenges of material recycling in additive construction, including the development of standard recycling processes and the evaluation of the impact of recycling on the mechanical properties of the printed structures, are not fully explored yet in the current literature [179,184]. Moreover, research regarding the use of locally extracted material mixtures toward higher sustainability would be necessary.

Pre- and post-construction sustainability: per the provided categories from the literature, given that the large-scale structures fabricated using AM techniques belong to residential or non-residential buildings, evaluating the post-construction sustainability of those structures in addition to pre-construction sustainability is critical. However, the majority of the current literature is focusing on environmental sustainability analyses at the pre-construction phase and efforts towards addressing post-construction sustainability are still minimal in the literature. Moreover, pre-construction decisions (e.g., the design of the AM infill pattern within the printed walls) can impact the insulation capabilities of such structures at the post-construction phase. Thus, an ideal construction planning methodology is expected to take into account the impact of such decisions in the post-construction phase.

Design for sustainability: Based on upcoming industrial revolution, we can locate the technological innovations which can contribute to transforming the design process into a more sustainability-aware procedure. This is since the design of structures can affect sustainability issues both for material selection and the construction process. Such design methodologies are also expected to consider the integration of building features, such as cables and electrical wiring, water pipes, insulation layers, etc., as well as the necessary support structures and their effects on the environment and material efficiency. In addition, the fragmentation of communications between experts can be reduced by using previously analyzed information. This can support designers in making design choices with a greater awareness of the influence on the result in regards to sustainability.

Sustainability versus quality: The most sustainable option might not necessarily provide the best quality. The potential tradeoffs between such decisions towards ensuring the quality and functional requirements of constructions should be considered. The majority of the existing research on sustainability in additive construction neglects this interrelation at the present moment.

Transportation of off-site constructed components: minimizing transportation efforts can clearly benefit the environment by reducing the carbon footprint [38]. Inventions for the on-site fabrication of structures are thus critical to minimize avoidable relocation/transportation of off-site constructed components.

Print quality has always been a challenge. Some quality aspects are due to failures of the print mechanism (e.g., mechanical failure of the extruder or possible clogging of the nozzle) but some are due to the intrinsic nature of the process (e.g., layer by layer mechanism which transfers variation in one layer to another, deformation of layers, etc.). Destructive tests are frequently adopted for quality control (generally after the print) however, non-destructive quality control mechanisms for the real-time in situ monitoring and control of such quality issues are increasing in popularity. These are mainly achieved through adopting cameras, advanced computer vision, artificial intelligence, and signal/image processing techniques.

7. Conclusions

This paper reviews the current progress and future challenges in the field of large-scale automated additive construction with a focus on the environmental sustainability (from three lenses of AM processes, material, and 3D-printed structures) as well as available and emerging robotic solutions, including hybrid and collaborative solutions. Among the various general challenges and research gaps highlighted, the following aspects are found to be less explored by the literature: (1) systematics approaches for sustainable planning in hybrid platforms and collaborative robots for additive construction; (2) decision support platforms to identify the most suitable AM process and compatible robotic solutions for a given application by characterizing the impact of various combinations of material, AM processes, and robotic solutions on the environment as well as the quality of the print; and (3) the evaluation of the lifecycle impacts and environmental sustainability of printed structures, especially in the post-construction phase in addition to the construction or pre-construction phases (the current focus of the literature). Moreover, with the majority of the literature focused on proof-of-concept studies, establishing a computational framework and standards is necessary to help promote this technology in the construction industry. It is expected that with future advancements and standardizations in this field, and consequently the reduction of additive construction costs and uncertainties, we will observe a significant proliferation of the AM in the construction industry.

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References

1. Kong, L.; Ambrosi, A.; Nasir, M.Z.M.; Guan, J.; Pumera, M. Smart Robots: Self-Propelled 3D-Printed "Aircraft Carrier" of Light-Powered Smart Micromachines for Large-Volume Nitroaromatic Explosives Removal. *Adv. Funct. Mater.* **2019**, *29*, 1903872. [CrossRef]
2. Du Pasquier, C.; Chen, T.; Tibbits, S.; Shea, K. Design and Computational Modeling of a 3D Printed Pneumatic Toolkit for Soft Robotics. *Soft Robot.* **2019**, *6*, 657–663. [CrossRef] [PubMed]
3. Juechter, V.; Franke, M.; Merenda, T.; Stich, A.; Körner, C.; Singer, R. Additive manufacturing of Ti-45Al-4Nb-C by selective electron beam melting for automotive applications. *Addit. Manuf.* **2018**, *22*, 118–126. [CrossRef]
4. Khosravani, M.R.; Reinicke, T. 3D-printed sensors: Current progress and future challenges. *Sens. Actuators A Phys.* **2020**, *305*, 111916. [CrossRef]
5. Mouser, V.H.M.; Levato, R.; Bonassar, L.J.; D'Lima, D.D.; Grande, D.A.; Klein, T.J.; Saris, D.B.F.; Zenobi-Wong, M.; Gawlitta, D.; Malda, J. Three-Dimensional Bioprinting and Its Potential in the Field of Articular Cartilage Regeneration. *Cartilage* **2017**, *8*, 327–340. [CrossRef] [PubMed]
6. Odaglia, P.; Voney, V.; Dillenburger, B.; Habert, G. Advances in Binder-Jet 3D Printing of Non-cementitious Materials. In *Second RILEM International Conference on Concrete and Digital Fabrication*; DC. RILEM Bookseries; Springer: Cham, Switzerland, 2020; Volume 28. [CrossRef]
7. Hildreth, O.J.; Nassar, A.R.; Chasse, K.R.; Simpson, T.W. Dissolvable Metal Supports for 3D Direct Metal Printing. *3D Print. Addit. Manuf.* **2016**, *3*, 90–97. [CrossRef]
8. Hansen, C.J. 3D and 4D printing of nanomaterials: Processing considerations for reliable printed nanocomposites. In *3D and 4D Printing of Polymer Nanocomposite Materials: Processes, Applications, and Challenges*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 25–44. [CrossRef]
9. Kulkarni, A.; Sorarù, G.D.; Pearce, J.M. Polymer-derived SiOC replica of material extrusion-based 3-D printed plastics. *Addit. Manuf.* **2020**, *32*, 100988. [CrossRef]
10. ASTM. F2792—12a. Standard Terminology for Additive Manufacturing Technologies. 2013. Available online: https://www.astm.org/DATABASE.CART/HISTORICAL/F2792-12.htm (accessed on 18 August 2021).
11. Mueller, R.P.; Howe, S.; Kochmann, D.; Ali, H.; Andersen, C.; Burgoyne, H.; Chambers, W.; Clinton, R.; De Kestellier, X.; Ebelt, K.; et al. Automated additive construction (AAC) for Earth and space using in-situ resources. In Proceedings of the Fifteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2016), American Society of Civil Engineers, Reston, VA, USA, 11–16 April 2016.
12. Siddika, A.; Al Mamun, A.; Ferdous, W.; Saha, A.K.; Alyousef, R. 3D-printed concrete: Applications, performance, and challenges. *J. Sustain. Cem. Mater.* **2020**, *9*, 127–164. [CrossRef]
13. Gagg, C.R. Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Eng. Fail. Anal.* **2014**, *40*, 114–140. [CrossRef]
14. Fernández, R.P.; Pardo, M.L. Offshore concrete structures. *Ocean Eng.* **2013**, *58*, 304–316. [CrossRef]
15. Kazemian, A.; Yuan, X.; Cochran, E.; Khoshnevis, B. Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. *Constr. Build. Mater.* **2017**, *145*, 639–647. [CrossRef]
16. Campos, A.; López, C.; Blanco, A.; Aguado, A. Effects of an internal sulfate attack and an alkali-aggregate reaction in a concrete dam. *Constr. Build. Mater.* **2018**, *166*, 668–683. [CrossRef]
17. Xue, J.; Briseghella, B.; Huang, F.; Nuti, C.; Tabatabai, H.; Chen, B. Review of ultra-high performance concrete and its application in bridge engineering. *Constr. Build. Mater.* **2020**, *260*, 119844. [CrossRef]
18. Horvath, A. Construction materials and the environment. *Annu. Rev. Environ. Resour.* **2004**, *29*, 181–204. [CrossRef]
19. Ghaffar, S.H.; Corker, J.; Fan, M. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Autom. Constr.* **2018**, *93*, 1–11. [CrossRef]
20. Paolini, A.; Kollmannsberger, S.; Rank, E. Additive manufacturing in construction: A review on processes, applications, and digital planning methods. *Addit. Manuf.* **2019**, *30*, 100894. [CrossRef]
21. Craveiro, F.; Duarte, J.P.; Bartolo, H.; Bartolo, P.J. Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0. *Autom. Constr.* **2019**, *103*, 251–267. [CrossRef]
22. Hamidi, F.; Aslani, F. Additive manufacturing of cementitious composites: Materials, methods, potentials, and challenges. *Constr. Build. Mater.* **2019**, *218*, 582–609. [CrossRef]
23. Al Rashid, A.; Khan, S.A.; Al-Ghamdi, S.G.; Koç, M. Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. *Autom. Constr.* **2020**, *118*, 103268. [CrossRef]

24. El-Sayegh, S.; Romdhane, L.; Manjikian, S. A critical review of 3D printing in construction: Benefits, challenges, and risks. *Arch. Civ. Mech. Eng.* **2020**, *20*, 34. [CrossRef]
25. Gharbia, M.; Chang-Richards, A.; Lu, Y.; Zhong, R.Y.; Li, H. Robotic technologies for on-site building construction: A systematic review. *J. Build. Eng.* **2020**, *32*, 101584. [CrossRef]
26. Alkhalidi, A.; Hatuqay, D. Energy efficient 3D printed buildings: Material and techniques selection worldwide study. *J. Build. Eng.* **2020**, *30*, 101286. [CrossRef]
27. Dixit, M.K. 3-D Printing in Building Construction: A Literature Review of Opportunities and Challenges of Reducing Life Cycle Energy and Carbon of Buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *290*, 012012. [CrossRef]
28. Bhardwaj, A.; Jones, S.Z.; Kalantar, N.; Pei, Z.; Vickers, J.; Wangler, T.; Zavattieri, P.; Zou, N. Additive Manufacturing Processes for Infrastructure Construction: A Review. *J. Manuf. Sci. Eng.* **2019**, *141*, 091010. [CrossRef]
29. Roberts, C.; Bourell, D. Precursor Additive Manufacturing Inventions. *JOM* **2018**, *70*, 2249–2253. [CrossRef]
30. Pegna, J. Exploratory investigation of solid freeform construction. *Autom. Constr.* **1997**, *5*, 427–437. [CrossRef]
31. Wolf, A.; Rosendahl, P.L.; Knaack, U. Additive manufacturing of clay and ceramic building components. *Autom. Constr.* **2022**, *133*, 103956. [CrossRef]
32. Furet, B.; Poullain, P.; Garnier, S. 3D printing for construction based on a complex wall of polymer-foam and concrete. *Addit. Manuf.* **2019**, *28*, 58–64. [CrossRef]
33. Bedarf, P.; Dutto, A.; Zanini, M.; Dillenburger, B. Foam 3D printing for construction: A review of applications, materials, and processes. *Autom. Constr.* **2021**, *130*, 103861. [CrossRef]
34. Li, R.Y.M. *An Economic Analysis on Automated Construction Safety*; Springer: Berlin/Heidelberg, Germany, 2018. [CrossRef]
35. Mohammad, M.; Masad, E.; Al-Ghamdi, S.G. 3D Concrete Printing Sustainability: A Comparative Life Cycle Assessment of Four Construction Method Scenarios. *Buildings* **2020**, *10*, 245. [CrossRef]
36. Khoshnevis, B.; Dutton, R. Innovative Rapid Prototyping Process Makes Large Sized, Smooth Surfaced Complex Shapes in a Wide Variety of Materials. *Mater. Technol.* **1998**, *13*, 53–56. [CrossRef]
37. Lim, S.; Buswell, R.; Le, T.; Austin, S.; Gibb, A.; Thorpe, T. Developments in construction-scale additive manufacturing processes. *Autom. Constr.* **2012**, *21*, 262–268. [CrossRef]
38. Mechtcherine, V.; Nerella, V.N.; Will, F.; Näther, M.; Otto, J.; Krause, M. Large-scale digital concrete construction—CONPrint3D concept for on-site, monolithic 3D-printing. *Autom. Constr.* **2019**, *107*, 102933. [CrossRef]
39. Colla, V.; Dini, E.; Canessa, E.; Fonda, C.; Zennaro, M. Large scale 3D printing: From deep sea to the moon. In *Low-Cost 3D Printing for Science, Education and Sustainable Development*; ICTP: Trieste, Italy, 2013; pp. 127–132.
40. Rael, R.; San Fratello, V. Developing concrete polymer building components for 3D printing. In *Integration through Computation: Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture, ACADIA*; Association for CAD in Architecture: Fargo, ND, USA, 2011; pp. 152–157.
41. Khoshnevis, B. Automated construction by contour crafting—Related robotics and information technologies. *Autom. Constr.* **2004**, *13*, 5–19. [CrossRef]
42. Smith, D. Fabrication construction components using layer manufacturing technology. *Constr. Res. Innov.* **2012**, *3*, 26–31. [CrossRef]
43. Lim, S.; Le, T.; Webster, J.; Buswell, R.; Austin, A.; Gibb, A.; Thorpe, T. Fabricating construction components using layer manufacturing technology. In *Global Innovation in Construction Conference 2009*; Loughborough University, Civil and Building Engineering: Loughborough, UK, 2018; pp. 512–520.
44. Nerella, V.; Krause, V.N.; Näther, M.; Mechtcherine, M. CONPrint3D—3D printing technology for onsite construction. *Concr. Aust.* **2016**, *42*, 36–39. [CrossRef]
45. Xia, M.; Nematollahi, B.; Sanjayan, J.G. Development of Powder-Based 3D Concrete Printing Using Geopolymers. In *3D Concrete Printing Technology*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 223–240. [CrossRef]
46. Rael, R.; Fratello, V.S. Bloom. Emerging Objects. Available online: https://emergingobjects.com/project/bloom-2/ (accessed on 14 May 2021).
47. Nematollahi, B.; Xia, M.; Sanjayan, M.X.A.J. Current Progress of 3D Concrete Printing Technologies. In Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC 2017), Taipei, Taiwan, 28 June–1 July 2017; pp. 260–267. [CrossRef]
48. Lowke, D.; Dini, E.; Perrot, A.; Weger, D.; Gehlen, C.; Dillenburger, B. Particle-bed 3D printing in concrete construction—Possibilities and challenges. *Cem. Concr. Res.* **2018**, *112*, 50–65. [CrossRef]
49. Cesaretti, G.; Dini, E.; De Kestelier, X.; Colla, V.; Pambaguian, L. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronaut.* **2014**, *93*, 430–450. [CrossRef]
50. Tay, Y.W.D.; Li, M.Y.; Tan, M.J. Effect of printing parameters in 3D concrete printing: Printing region and support structures. *J. Mater. Process. Technol.* **2019**, *271*, 261–270. [CrossRef]
51. Liu, Z.; Li, M.; Weng, Y.; Qian, Y.; Wong, T.N.; Tan, M.J. Modelling and parameter optimization for filament deformation in 3D cementitious material printing using support vector machine. *Compos. Part B Eng.* **2020**, *193*, 108018. [CrossRef]
52. Tay, Y.W.D.; Panda, B.; Paul, S.C.; Mohamed, N.A.N.; Tan, M.J.; Leong, K.F. 3D printing trends in building and construction industry: A review. *Virtual Phys. Prototyp.* **2017**, *12*, 261–276. [CrossRef]

53. Paul, S.C.; Tay, Y.W.D.; Panda, B.; Tan, M.J. Fresh and hardened properties of 3D printable cementitious materials for building and construction. *Arch. Civ. Mech. Eng.* **2018**, *18*, 311–319. [CrossRef]
54. Lu, B.; Weng, Y.; Li, M.; Qian, Y.; Leong, K.F.; Tan, M.J.; Qian, S. A systematical review of 3D printable cementitious materials. *Constr. Build. Mater.* **2019**, *207*, 477–490. [CrossRef]
55. Panda, B.; Tan, M.-J. Rheological behavior of high volume fly ash mixtures containing micro silica for digital construction application. *Mater. Lett.* **2019**, *237*, 348–351. [CrossRef]
56. Hambach, M.; Volkmer, D. Properties of 3D-printed fiber-reinforced Portland cement paste. *Cem. Concr. Compos.* **2017**, *79*, 62–70. [CrossRef]
57. Ma, G.; Li, Z.; Wang, L.; Wang, F.; Sanjayan, J. Mechanical anisotropy of aligned fiber reinforced composite for extrusion-based 3D printing. *Constr. Build. Mater.* **2019**, *202*, 770–783. [CrossRef]
58. Nematollahi, B.; Vijay, P.; Sanjayan, J.; Nazari, A.; Xia, M.; Nerella, V.N.; Mechtcherine, V. Effect of Polypropylene Fibre Addition on Properties of Geopolymers Made by 3D Printing for Digital Construction. *Materials* **2018**, *11*, 2352. [CrossRef]
59. Kosson, M.; Brown, L.; Sanchez, F. Early-Age Performance of 3D Printed Carbon Nanofiber and Carbon Microfiber Cement Composites. *Transp. Res. Rec.* **2020**, *2674*, 10–20. [CrossRef]
60. Nguyen-Van, V.; Choudhry, N.K.; Panda, B.; Nguyen-Xuan, H.; Tran, P. Performance of concrete beam reinforced with 3D printed Bioinspired primitive scaffold subjected to three-point bending. *Autom. Constr.* **2022**, *134*, 104060. [CrossRef]
61. Heever, G.; Bester, M.; Kruger, F.; Zijl, J. Numerical modelling strategies for reinforced 3D concrete printed elements. *Addit. Manuf.* **2022**, *50*, 102569.
62. Wu, Z.; Memari, A.M.; Duarte, J.P. State of the Art Review of Reinforcement Strategies and Technologies for 3D Printing of Concrete. *Energies* **2022**, *15*, 360. [CrossRef]
63. Asprone, D.; Menna, C.; Bos, F.P.; Salet, T.A.; Mata-Falcón, J.; Kaufmann, W. Rethinking reinforcement for digital fabrication with concrete. *Cem. Concr. Res.* **2018**, *112*, 111–121. [CrossRef]
64. Bos, F.P.; Ahmed, Z.Y.; Jutinov, E.R.; Salet, T.A.M. Experimental Exploration of Metal Cable as Reinforcement in 3D Printed Concrete. *Materials* **2017**, *10*, 1314. [CrossRef]
65. Winsun. Demonstrating the Viability of 3D Printing at Construction Scale. World Economic Forum. 2016. Available online: https://futureofconstruction.org/case/winsun/ (accessed on 14 September 2021).
66. Khoshnevis, B.; Hwang, D.; Yao, K.T.; Yeh, Z. Mega-scale fabrication by Contour Crafting. *Int. J. Ind. Syst. Eng.* **2006**, *1*, 301–320. [CrossRef]
67. Figueiredo, S.C.; Copuroglu, O.; Schlangen, E. Effect of viscosity modifier admixture on Portland cement paste hydration and microstructure. *Constr. Build. Mater.* **2019**, *212*, 818–840. [CrossRef]
68. Reales, O.A.M.; Duda, P.; Silva, E.C.; Paiva, M.D.; Filho, R.D.T. Nanosilica particles as structural buildup agents for 3D printing with Portland cement pastes. *Constr. Build. Mater.* **2019**, *219*, 91–100. [CrossRef]
69. Kazemian, A.; Yuan, X.; Meier, R.; Khoshnevis, B. Performance-Based Testing of Portland Cement Concrete for Construction-Scale 3D Printing. In *3D Concrete Printing Technology*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 13–35. [CrossRef]
70. Khalil, N.; Aouad, G.; El Cheikh, K.; Rémond, S. Use of calcium sulfoaluminate cements for setting control of 3D-printing mortars. *Constr. Build. Mater.* **2017**, *157*, 382–391. [CrossRef]
71. Shakor, P.; Sanjayan, J.; Nazari, A.; Nejadi, S. Modified 3D printed powder to cement-based material and mechanical properties of cement scaffold used in 3D printing. *Constr. Build. Mater.* **2017**, *138*, 398–409. [CrossRef]
72. Chen, Y.; Figueiredo, S.C.; Yalçinkaya, Ç.; Çopuroğlu, O.; Veer, F.; Schlangen, E. The Effect of Viscosity-Modifying Admixture on the Extrudability of Limestone and Calcined Clay-Based Cementitious Material for Extrusion-Based 3D Concrete Printing. *Materials* **2019**, *12*, 1374. [CrossRef]
73. Sun, X.; Wang, Q.; Wang, H.; Chen, L. Influence of multi-walled nanotubes on the fresh and hardened properties of a 3D printing PVA mortar ink. *Constr. Build. Mater.* **2020**, *247*, 118590. [CrossRef]
74. Wang, L.; Tian, Z.; Ma, G.; Zhang, M. Interlayer bonding improvement of 3D printed concrete with polymer modified mortar: Experiments and molecular dynamics studies. *Cem. Concr. Compos.* **2020**, *110*, 103571. [CrossRef]
75. Ding, T.; Xiao, J.; Zou, S.; Wang, Y. Hardened properties of layered 3D printed concrete with recycled sand. *Cem. Concr. Compos.* **2020**, *113*, 103724. [CrossRef]
76. Muthukrishnan, S.; Ramakrishnan, S.; Sanjayan, J. Technologies for improving buildability in 3D concrete printing. *Cem. Concr. Compos.* **2021**, *122*, 104144. [CrossRef]
77. Zareiyan, B.; Khoshnevis, B. Interlayer adhesion and strength of structures in Contour Crafting—Effects of aggregate size, extrusion rate, and layer thickness. *Autom. Constr.* **2017**, *81*, 112–121. [CrossRef]
78. Sanjayan, J.G.; Nematollahi, B.; Xia, M.; Marchment, T. Effect of surface moisture on inter-layer strength of 3D printed concrete. *Constr. Build. Mater.* **2018**, *172*, 468–475. [CrossRef]
79. Tay, Y.W.D.; Ting, G.H.A.; Qian, Y.; Panda, B.; He, L.; Tan, M.J. Time gap effect on bond strength of 3D-printed concrete. *Virtual Phys. Prototyp.* **2019**, *14*, 104–113. [CrossRef]
80. Panda, B.; Paul, S.C.; Mohamed, N.A.N.; Tay, Y.W.D.; Tan, M.J. Measurement of tensile bond strength of 3D printed geopolymer mortar. *J. Int. Meas. Confed.* **2018**, *113*, 108–116. [CrossRef]
81. Xu, J.; Zhang, G.; Hou, Z.; Wang, J.; Liang, J.; Bao, X.; Yang, W.; Wang, W. Advances in Multi-robotic Welding Techniques: A Review. *Int. J. Mech. Eng. Robot. Res.* **2020**, *9*, 421–428. [CrossRef]

82. Chea, C.P.; Bai, Y.; Pan, X.; Arashpour, M.; Xie, Y. An integrated review of automation and robotic technologies for structural prefabrication and construction. *Transp. Saf. Environ.* **2020**, *2*, 81–96. [CrossRef]
83. Khan, A.; Mineo, C.; Dobie, G.; Macleod, C.; Pierce, G. Vision guided robotic inspection for parts in manufacturing and remanufacturing industry. *J. Remanuf.* **2021**, *11*, 49–70. [CrossRef]
84. Faccio, M.; Bottin, M.; Rosati, G. Collaborative and traditional robotic assembly: A comparison model. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 1355–1372. [CrossRef]
85. Wang, Z.; Li, H.; Yang, X. Vision-based robotic system for on-site construction and demolition waste sorting and recycling. *J. Build. Eng.* **2020**, *32*, 101769. [CrossRef]
86. Björnsson, A.; Jonsson, M.; Johansen, K. Automated material handling in composite manufacturing using pick-and-place systems—A review. *Robot. Comput. Manuf.* **2018**, *51*, 222–229. [CrossRef]
87. Bhatt, P.M.; Kabir, A.M.; Malhan, K.R.; Shah, B.; Shembekar, A.V.; Yoon, Y.J.; Gupta, S.K. A Robotic Cell for Mul-ti-Resolution Additive Manufacturing. In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 20–24 May 2019; pp. 2800–2807. [CrossRef]
88. Evjemo, L.D.; Gjerstad, T.; Grøtli, E.I.; Sziebig, G. Trends in Smart Manufacturing: Role of Humans and Industrial Robots in Smart Factories. *Curr. Robot. Rep.* **2020**, *1*, 35–41. [CrossRef]
89. Labonnote, N.; Rønnquist, A.; Manum, B.; Rüther, P. Additive construction: State-of-the-art, challenges and opportunities. *Autom. Constr.* **2016**, *72*, 347–366. [CrossRef]
90. Li, L.; Haghighi, A.; Yang, Y. A novel 6-axis hybrid additive-subtractive manufacturing process: Design and case studies. *J. Manuf. Process.* **2018**, *33*, 150–160. [CrossRef]
91. Chandak, L.P.; Junghare, A.; Naik, T.; Ukani, N.; Chakole, S. Mobile Gantry Robot for Pick & Place Application. In *2020 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*; IEEE: Piscataway, NJ, USA, 2020; pp. 1–5. [CrossRef]
92. Khoshnevis, B.; Russell, R.; Kwon, H.; Bukkapatnam, S. Crafting large prototypes. *IEEE Robot. Autom. Mag.* **2001**, *8*, 33–42. [CrossRef]
93. Panda, B.; Lim, J.H.; Tan, M.J. Mechanical properties and deformation behaviour of early age concrete in the context of digital construction. *Compos. Part B Eng.* **2019**, *165*, 563–571. [CrossRef]
94. Freire, T.; Brun, F.; Mateus, A.; Gaspar, F. 3D Printing Technology in the Construction Industry. In *Advances in Science, Technology and Innovation*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 157–167.
95. COBOD. Modular 3D Construction Printer. Available online: https://cobod.com/ (accessed on 27 September 2021).
96. Apis-Cor.com. Apis-Cor 3D Concrete Printing. Available online: https://www.apis-cor.com/ (accessed on 27 September 2021).
97. Davtalab, O.; Kazemian, A.; Khoshnevis, B. Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. *Autom. Constr.* **2018**, *89*, 13–23. [CrossRef]
98. Toklu, Y.C.; Bekdaş, G.; Geem, Z.W. Harmony Search Optimization of Nozzle Movement for Additive Manufacturing of Concrete Structures and Concrete Elements. *Appl. Sci.* **2020**, *10*, 4413. [CrossRef]
99. Zhang, J.; Khoshnevis, B. Optimal machine operation planning for construction by Contour Crafting. *Autom. Constr.* **2013**, *29*, 50–67. [CrossRef]
100. Kazemian, A.; Yuan, X.; Davtalab, O.; Khoshnevis, B. Computer vision for real-time extrusion quality monitoring and control in robotic construction. *Autom. Constr.* **2019**, *101*, 92–98. [CrossRef]
101. Gaudillière, N.; Duballet, R.; Bouyssou, C.; Mallet, A.; Roux, P.; Zakeri, M.; Dirrenberger, J. Large-Scale Additive Manufacturing of Ultra-High-Performance Concrete of Integrated Formwork for Truss-Shaped Pillars. In *Robotic Fabrication in Architecture, Art and Design 2018*; Springer: Cham, Switzerland, 2019; pp. 459–472. [CrossRef]
102. EnvisionTEC. Viridis3D. Available online: https://envisiontec.com/de/3d-printers/ (accessed on 27 September 2021).
103. Gosselin, C.; Duballet, R.; Roux, P.; Gaudillière, N.; Dirrenberger, J.; Morel, P. Large-scale 3D printing of ultra-high performance concrete—A new processing route for architects and builders. *Mater. Des.* **2016**, *100*, 102–109. [CrossRef]
104. Kwon, H.; Eichenhofer, M.; Kyttas, T.; Dillenburger, B. Digital Composites: Robotic 3D Printing of Continuous Carbon Fiber-Reinforced Plastics for Functionally-Graded Building Components. In *Robotic Fabrication in Architecture, Art and Design 2018*; Springer: Cham, Switzerland, 2019; pp. 363–376. [CrossRef]
105. Chan, S.; Pennings, R.M.; Edwards, L.; Franks, G.V. 3D printing of clay for decorative architectural applications: Effect of solids volume fraction on rheology and printability. *Addit. Manuf.* **2020**, *35*, 101335. [CrossRef]
106. Bosscher, P.; Williams, R.L., II; Bryson, L.S.; Castro-Lacouture, D. Cable-suspended robotic contour crafting system. *Autom. Constr.* **2007**, *17*, 45–55. [CrossRef]
107. Barnett, E.; Gosselin, C. Large-scale 3D printing with a cable-suspended robot. *Addit. Manuf.* **2015**, *7*, 27–44. [CrossRef]
108. Shahmiri, F.; Gentry, R. A Survey of Cable-Suspended Parallel Robots and their Applications in Architecture and Construction. In Proceedings of the Congress of the Iberoamerican Society of Digital Graphics, Buenos Aires, Argentina, 9–11 November 2016; pp. 914–920. [CrossRef]
109. Williams, R.L.; Albus, J.S.; Bostelman, R.V. Self-contained automated construction deposition system. *Autom. Constr.* **2004**, *13*, 393–407. [CrossRef]
110. Izard, J.-B.; Dubor, A.; Hervé, P.-E.; Cabay, E.; Culla, D.; Rodriguez, M.; Barrado, M. Large-scale 3D printing with cable-driven parallel robots. *Constr. Robot.* **2017**, *1*, 69–76. [CrossRef]

111. Jung, J. Workspace and Stiffness Analysis of 3D Printing Cable-Driven Parallel Robot with a Retractable Beam-Type End-Effector. *Robotics* **2020**, *9*, 65. [CrossRef]
112. WASP. BigDelta WASP 12m. Available online: https://www.3dwasp.com/stampante-3d-gigante-bigdelta-wasp-12mt/ (accessed on 28 September 2021).
113. Chesser, P.; Post, B.; Lind, R.; Roschli, A.; Atkins, C.; Boulger, A.; Mhatre, P.; Lloyd, P. Skybaam large-scale fieldable deposition platform system architecture. In Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium—An Additive Manufacturing Conference, Austin, TX, USA, 12–14 August 2019; pp. 1558–1567.
114. Chesser, P.C.; Wang, P.L.; Vaughan, J.E.; Lind, R.F.; Post, B.K. Kinematics of a Cable-Driven Robotic Platform for Large-Scale Additive Manufacturing. *J. Mech. Robot.* **2022**, *14*, 021010. [CrossRef]
115. Bulgakov, A.G.; Pakhomova, E.G. Coordination of construction manipulation robotic system using UAV. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *789*, 012007. [CrossRef]
116. Shahmoradi, J.; Talebi, E.; Roghanchi, P.; Hassanalian, M. A Comprehensive Review of Applications of Drone Technology in the Mining Industry. *Drones* **2020**, *4*, 34. [CrossRef]
117. Lombard, N.F.; Byland, W.W.; Henry, G.J.; Liga, M.V.; Price, V.N. Seeing from above, What's below: How Drones Can Be Used in Pipeline Design and Construction. in Pipelines 2020: Utility Engineering, Surveying, and Multidisciplinary Topics. In Proceedings of the Sessions of the Pipelines 2020 Conference, American Society of Civil Engineers, Reston, VA, USA, 9–12 August 2020; pp. 392–401.
118. Ollero, A.; Heredia, G.; Franchi, A.; Antonelli, G.; Kondak, K.; Sanfeliu, A.; Viguria, A.; Martinez-de Dios, J.R.; Pierri, F.; Cortés, J.; et al. The AEROARMS Project: Aerial Robots with Advanced Manipulation Capabilities for Inspection and Maintenance. *IEEE Robot. Autom. Mag.* **2018**, *25*, 12–23. [CrossRef]
119. Mirjan, A.; Augugliaro, F.; D'Andrea, R.; Gramazio, F.; Kohler, M. Building a Bridge with Flying Robots. In *Robotic Fabrication in Architecture, Art and Design 2016*; Springer: Cham, Switzerland, 2016; pp. 34–47.
120. Hunt, G.; Mitzalis, F.; Alhinai, T.; Hooper, P.A.; Kovac, M. 3D printing with flying robots. In Proceedings of the IEEE International Conference on Robotics and Automation, Hong Kong, China, 31 May–5 June 2014; pp. 4493–4499. [CrossRef]
121. Dams, B.; Sareh, S.; Zhang, K.; Shepherd, P.; Kovac, M.; Ball, R.J. Aerial additive building manufacturing: Three-dimensional printing of polymer structures using drones. *Proc. Inst. Civ. Eng. Constr. Mater.* **2020**, *173*, 3–14. [CrossRef]
122. Vélez, M.; Toala, E.; Zagal, J.C. Koala 3D: A continuous climbing 3D printer. *Robot. Comput. Manuf.* **2020**, *64*, 101950. [CrossRef]
123. Howe, A.S.; Wilcox, B.; McQuin, C.; Mittman, D.; Townsend, J.; Polit-Casillas, R.; Litwin, T. Modular Additive Construction Using Native Materials. in Earth and Space 2014: Engineering for Extreme Environments. In Proceedings of the 14th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments, Reston, VA, USA, 27–29 October 2014; pp. 301–312.
124. Keating, S.J.; Leland, J.C.; Cai, L.; Oxman, N. Toward site-specific and self-sufficient robotic fabrication on architectural scales. *Sci. Robot.* **2017**, *2*, 8986. [CrossRef]
125. Tiryaki, M.E.; Zhang, X.; Pham, Q.-C. Printing-while-moving: A new paradigm for large-scale robotic 3D Printing. In Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Macau, China, 4–8 November 2019; pp. 2286–2291. [CrossRef]
126. Zhang, X.; Li, M.; Lim, J.H.; Weng, Y.; Tay, Y.W.D.; Pham, H.; Pham, Q.-C. Large-scale 3D printing by a team of mobile robots. *Autom. Constr.* **2018**, *95*, 98–106. [CrossRef]
127. Sutjipto, S.; Tish, D.; Paul, G.; Vidal-Calleja, T.; Schork, T. Towards Visual Feedback Loops for Robot-Controlled Additive Manufacturing. In *Robotic Fabrication in Architecture, Art and Design 2019*; Springer: Cham, Switzerland, 2019; pp. 85–97. [CrossRef]
128. Dörfler, K.; Hack, N.; Sandy, T.; Giftthaler, M.; Lussi, M.; Walzer, A.N.; Buchli, J.; Gramazio, F.; Kohler, M. Mobile robotic fabrication beyond factory conditions: Case study Mesh Mould wall of the DFAB HOUSE. *Constr. Robot.* **2019**, *3*, 53–67. [CrossRef]
129. Kontovourkis, O.; Phocas, M.C.; Tryfonos, G.; Georgiou, C. Multi-axis 3D printing of material reduced shell structures on a reconfigurable supporting system using topology optimization principles. *Procedia Manuf.* **2020**, *44*, 379–386. [CrossRef]
130. Kontovourkis, O.; Tryfonos, G.; Georgiou, C. Robotic additive manufacturing (RAM) with clay using topology optimization principles for toolpath planning: The example of a building element. *Arch. Sci. Rev.* **2020**, *63*, 105–118. [CrossRef]
131. Kontovourkis, O.; Tryfonos, G. Robotic 3D clay printing of prefabricated non-conventional wall components based on a parametric-integrated design. *Autom. Constr.* **2020**, *110*, 103005. [CrossRef]
132. Dritsas, S.; Vijay, Y.; Dimopoulou, M.; Sanadiya, N.; Fernandez, J.G. An Additive and Subtractive Process for Manufacturing with Natural Composites. In *Robotic Fabrication in Architecture, Art and Design 2018*; Springer: Cham, Switzerland, 2019; pp. 181–191. [CrossRef]
133. Arai, T.; Pagello, E.; Parker, L. Advances in multirobot systems. *IEEE Trans. Robot. Autom.* **2002**, *18*, 655–661. [CrossRef]
134. Lindsey, Q.; Mellinger, D.; Kumar, V. Construction of Cubic Structures with Quadrotor Teams. *Robot. Sci. Syst.* **2012**, *7*, 177–184. [CrossRef]
135. Augugliaro, F.; Lupashin, S.; Hamer, M.; Male, C.; Hehn, M.; Mueller, M.W.; Willmann, J.S.; Gramazio, F.; Kohler, M.; D'Andrea, R. The flight assembled architecture installation: Cooperative construction with flying machines. *IEEE Control. Syst. Mag.* **2014**, *34*, 46–64.

136. Dogar, M.R.; Knepper, R.A.; Spielberg, A.; Choi, C.; Christensen, H.I.; Rus, D. Multi-scale assembly with robot teams. *Int. J. Robot. Res.* **2015**, *34*, 1645–1659. [CrossRef]
137. Kayser, M.; Cai, L.; Bader, C.; Falcone, S.; Inglessis, N.; Darweesh, B.; Costa, J.; Oxman, N. FIBERBOTS: Design and Digital Fabrication of Tubular Structures Using Robot Swarms. In *Robotic Fabrication in Architecture, Art and Design 2018*; Springer: Cham, Switzerland, 2019; pp. 285–296. [CrossRef]
138. Estrada, R.D.; Kannenberg, F.; Wagner, H.J.; Yablonina, M.; Menges, A. Spatial winding: Cooperative heterogeneous multi-robot system for fibrous structures. *Constr. Robot.* **2020**, *4*, 205–215. [CrossRef]
139. Vasey, L.; Felbrich, B.; Prado, M.; Tahanzadeh, B.; Menges, A. Physically distributed multi-robot coordination and collaboration in construction. *Constr. Robot.* **2020**, *4*, 3–18. [CrossRef]
140. Shen, H.; Pan, L.; Qian, J. Research on large-scale additive manufacturing based on multi-robot collaboration technology. *Addit. Manuf.* **2019**, *30*, 100906. [CrossRef]
141. Sustarevas, J.; Tan, K.X.B.; Gerber, D.; Stuart-Smith, R.; Pawar, V.M. YouWasps: Towards Autonomous Multi-Robot Mobile Deposition for Construction. In Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Macau, China, 4–8 November 2019; pp. 2320–2327. [CrossRef]
142. Poudel, L.; Zhou, W.; Sha, Z. A Generative Approach for Scheduling Multi-Robot Cooperative Three-Dimensional Printing. *J. Comput. Inf. Sci. Eng.* **2020**, *20*, 061011. [CrossRef]
143. Poudel, L.; Zhou, W.; Sha, Z. Resource-Constrained Scheduling for Multi-Robot Cooperative Three-Dimensional Printing. *J. Mech. Des.* **2021**, *143*, 072002, Transactions of the ASME. [CrossRef]
144. Fascetti, A.; Latteur, P.; Lim, S.H. Ground-based automated construction of droxel structures: An experimental approach. *Autom. Constr.* **2021**, *131*, 103899. [CrossRef]
145. Buswell, R.; Soar, R.; Gibb, A.; Thorpe, A. Freeform Construction: Mega-scale Rapid Manufacturing for construction. *Autom. Constr.* **2007**, *16*, 224–231. [CrossRef]
146. Buswell, R.; Thorpe, A.; Soar, R.; Gibb, A. Design, data and process issues for mega-scale rapid manufacturing machines used for construction. *Autom. Constr.* **2008**, *17*, 923–929. [CrossRef]
147. Hwang, D.; Khoshnevis, B. An Innovative Construction Process-Contour Crafting (CC). In Proceedings of the 22nd International Symposium on Automation and Robotics in Construction (ISARC), Ferrara, Italy, 11–14 September 2005; Volume 1, pp. 1–6. [CrossRef]
148. Gardiner, J.; Janssen, S.; Kirchner, S.J.A.N. A Realization of a Construction Scale Robotic System for 3D Printing of Complex Formwork. In Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC), Auburn, AL, USA, 18–21 July 2016; pp. 515–521. [CrossRef]
149. Ou, Y.; Bao, D.-W.; Zhu, G.-Q.; Luo, D. Additive Fabrication of Large-Scale Customizable Formwork Using Robotic Fiber-Reinforced Polymer Winding. *3D Print. Addit. Manuf.* **2021**, *9*, 109–121. [CrossRef]
150. Jipa, A.; Dillenburger, B. 3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications. *3D Print. Addit. Manuf.* **2022**, *9*, 84–107. [CrossRef]
151. Lim, S.; Buswell, R.A.; Valentine, P.J.; Piker, D.; Austin, S.A.; De Kestelier, X. Modelling curved-layered printing paths for fabricating large-scale construction components. *Addit. Manuf.* **2016**, *12*, 216–230. [CrossRef]
152. Chong, L.; Ramakrishna, S.; Singh, S. A review of digital manufacturing-based hybrid additive manufacturing processes. *Int. J. Adv. Manuf. Technol.* **2018**, *95*, 2281–2300. [CrossRef]
153. Merklein, M.; Junker, D.; Schaub, A.; Neubauer, F. Hybrid Additive Manufacturing Technologies—An Analysis Regarding Potentials and Applications. *Phys. Procedia* **2016**, *83*, 549–559. [CrossRef]
154. Sealy, M.P.; Madireddy, G.; Williams, R.E.; Rao, P.; Toursangsaraki, M. Hybrid Processes in Additive Manufacturing. *J. Manuf. Sci. Eng.* **2018**, *140*, 060801. [CrossRef]
155. Khosravani, M.R.; Reinicke, T. On the environmental impacts of 3D printing technology. *Appl. Mater. Today* **2020**, *20*, 100689. [CrossRef]
156. Hager, I.; Golonka, A.; Putanowicz, R. 3D Printing of Buildings and Building Components as the Future of Sustainable Construction? *Procedia Eng.* **2016**, *151*, 292–299. [CrossRef]
157. Agustí-Juan, I.; Müller, F.; Hack, N.; Wangler, T.; Habert, G. Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall. *J. Clean. Prod.* **2017**, *154*, 330–340. [CrossRef]
158. *ISO 14044:2006*; Environmental Management—Life Cycle Assessement—Requirements and Guidelines, ISO 14044. International Organization for Standardization: Geneva, Switzerland, 2006.
159. Muñoz, I.; Alonso-Madrid, J.; Menéndez-Muñiz, M.; Uhart, M.; Canou, J.; Martin, C.; Fabritius, M.; Calvo, L.; Poudelet, L.; Cardona, R.; et al. Life cycle assessment of integrated additive–subtractive concrete 3D printing. *Int. J. Adv. Manuf. Technol.* **2021**, *112*, 2149–2159. [CrossRef]
160. Batikha, M.; Jotangia, R.; Baaj, M.Y.; Mousleh, I. 3D concrete printing for sustainable and economical construction: A comparative study. *Autom. Constr.* **2022**, *134*, 104087. [CrossRef]
161. Kuzmenko, K.; Gaudillière, N.; Feraille, A.; Dirrenberger, J.; Baverel, O. Assessing the Environmental Viability of 3D Concrete Printing Technology. In *Impact: Design with All Senses*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 517–528. [CrossRef]

162. Weng, Y.; Li, M.; Ruan, S.; Wong, T.N.; Tan, M.J.; Yeong, K.L.O.; Qian, S. Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *J. Clean. Prod.* **2020**, *261*, 121245. [CrossRef]
163. Long, W.-J.; Lin, C.; Tao, J.-L.; Ye, T.-H.; Fang, Y. Printability and particle packing of 3D-printable limestone calcined clay cement composites. *Constr. Build. Mater.* **2021**, *282*, 122647. [CrossRef]
164. Muñiz, M.M.; Chantin, M.; Vintila, C.R.; Fabritius, M.; Martin, C.; Calvo, L.; Poudelet, L.; Canou, J.; Uhart, M.; Papacharalampopoulos, A.; et al. Concrete hybrid manufacturing: A machine architecture. *Procedia CIRP* **2021**, *97*, 51–58. [CrossRef]
165. Haghighi, A.; Mohammed, A.; Wang, L. Energy Efficient Multi-Robotic 3D Printing for Large-Scale Construction—Framework, Challenges, and a Systematic Approach. In Proceedings of the International Manufacturing Science and Engineering Conferencem, Online, 21–25 June 2021. [CrossRef]
166. Alhumayani, H.; Gomaa, M.; Soebarto, V.; Jabi, W. Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete. *J. Clean. Prod.* **2020**, *270*, 122463. [CrossRef]
167. Weng, Y.; Ruan, S.; Li, M.; Mo, L.; Unluer, C.; Tan, M.J.; Qian, S. Feasibility study on sustainable magnesium potassium phosphate cement paste for 3D printing. *Constr. Build. Mater.* **2019**, *221*, 595–603. [CrossRef]
168. Khan, M.S.; Sanchez, F.; Zhou, H. 3-D printing of concrete: Beyond horizons. *Cem. Concr. Res.* **2020**, *133*, 106070. [CrossRef]
169. Perrot, A.; Rangeard, D.; Courteille, E. 3D Printing of Earth-Based Materials: Processing Aspects. In *Construction and Building Materials*; Elsevier: Amsterdam, The Netherlands, 2018; Volume 172, pp. 670–676.
170. Gounni, A.; Louahlia, H. Dynamic behavior and economic analysis of sustainable building integrating cob and phase change materials. *Constr. Build. Mater.* **2021**, *262*, 120795. [CrossRef]
171. de Brito, J.; Kurda, R. The past and future of sustainable concrete: A critical review and new strategies on cement-based materials. *J. Clean. Prod.* **2020**, *281*, 123558. [CrossRef]
172. Panda, B.; Paul, S.C.; Hui, L.J.; Tay, Y.W.D.; Tan, M.J. Additive manufacturing of geopolymer for sustainable built environment. *J. Clean. Prod.* **2017**, *167*, 281–288. [CrossRef]
173. Panda, B.; Paul, S.C.; Tan, M.J. Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material. *Mater. Lett.* **2017**, *209*, 146–149. [CrossRef]
174. Yao, Y.; Hu, M.; Di Maio, F.; Cucurachi, S. Life cycle assessment of 3D printing geo-polymer concrete: An ex-ante study. *J. Ind. Ecol.* **2020**, *24*, 116–127. [CrossRef]
175. Long, W.-J.; Tao, J.-L.; Lin, C.; Gu, Y.-C.; Mei, L.; Duan, H.-B.; Xing, F. Rheology and buildability of sustainable cement-based composites containing micro-crystalline cellulose for 3D-printing. *J. Clean. Prod.* **2019**, *239*, 118054. [CrossRef]
176. Bhattacherjee, S.; Basavaraj, A.S.; Rahul, A.; Santhanam, M.; Gettu, R.; Panda, B.; Schlangen, E.; Chen, Y.; Copuroglu, O.; Ma, G.; et al. Sustainable materials for 3D concrete printing. *Cem. Concr. Compos.* **2021**, *122*, 104156. [CrossRef]
177. Dey, D.; Srinivas, D.; Panda, B.; Suraneni, P.; Sitharam, T. Use of industrial waste materials for 3D printing of sustainable concrete: A review. *J. Clean. Prod.* **2022**, *340*, 130749. [CrossRef]
178. Ting, G.H.A.; Tay, Y.W.D.; Qian, Y.; Tan, M.J. Utilization of recycled glass for 3D concrete printing: Rheological and mechanical properties. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 994–1003. [CrossRef]
179. Xiao, J.; Zou, S.; Yu, Y.; Wang, Y.; Ding, T.; Zhu, Y.; Yu, J.; Li, S.; Duan, Z.; Wu, Y.; et al. 3D recycled mortar printing: System development, process design, material properties and on-site printing. *J. Build. Eng.* **2020**, *32*, 101779. [CrossRef]
180. Lin, A.; Tan, Y.K.; Wang, C.-H.; Kua, H.W.; Taylor, H. Utilization of waste materials in a novel mortar–polymer laminar composite to be applied in construction 3D-printing. *Compos. Struct.* **2020**, *253*, 112764. [CrossRef]
181. Rehman, A.U.; Lee, S.-M.; Kim, J.-H. Use of municipal solid waste incineration ash in 3D printable concrete. *Process Saf. Environ. Prot.* **2020**, *142*, 219–228. [CrossRef]
182. Bai, G.; Wang, L.; Ma, G.; Sanjayan, J.; Bai, M. 3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates. *Cem. Concr. Compos.* **2021**, *120*, 104037. [CrossRef]
183. Lu, B.; Zhu, W.; Weng, Y.; Liu, Z.; Yang, E.-H.; Leong, K.F.; Tan, M.-J.; Wong, T.N.; Qian, S. Study of MgO-activated slag as a cementless material for sustainable spray-based 3D printing. *J. Clean. Prod.* **2020**, *258*, 120671. [CrossRef]
184. Han, Y.; Yang, Z.; Ding, T.; Xiao, J. Environmental and economic assessment on 3D printed buildings with recycled concrete. *J. Clean. Prod.* **2021**, *278*, 123884. [CrossRef]
185. Arunothayan, A.R.; Nematollahi, B.; Ranade, R.; Khayat, K.H.; Sanjayan, J.G. Digital fabrication of eco-friendly ultra-high performance fiber-reinforced concrete. *Cem. Concr. Compos.* **2022**, *125*, 104281. [CrossRef]
186. Liu, J.; Li, S.; Gunasekara, C.; Fox, K.; Tran, P. 3D-printed concrete with recycled glass: Effect of glass gradation on flexural strength and microstructure. *Constr. Build. Mater.* **2022**, *314*, 125561. [CrossRef]
187. Yang, Y.; Che, H. Recycling of aggregate micro fines as a partial replacement for fly ash in 3D printing cementitious materials. *Constr. Build. Mater.* **2022**, *321*, 126372. [CrossRef]
188. United Nations Environment Programme. Sustainable Buildings. 2021. Available online: https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/sustainable-buildings (accessed on 20 July 2021).
189. De Schutter, G.; Lesage, K.; Mechtcherine, V.; Nerella, V.N.; Habert, G.; Agusti-Juan, I. Vision of 3D printing with concrete—Technical, economic and environmental potentials. *Cem. Concr. Res.* **2018**, *112*, 25–36. [CrossRef]
190. Kaszyńska, M.; Skibicki, S.; Hoffmann, M. 3D Concrete Printing for Sustainable Construction. *Energies* **2020**, *13*, 6351. [CrossRef]

191. Biswas, K.; Rose, J.; Eikevik, L.; Guerguis, M.; Enquist, P.; Lee, B.; Love, L.; Green, J.; Jackson, R. Additive Manufacturing Integrated Energy—Enabling Innovative Solutions for Buildings of the Future. *J. Sol. Energy Eng.* **2017**, *139*, 015001. [CrossRef]
192. Agustí-Juan, I.; Jipa, A.; Habert, G. Environmental assessment of multi-functional building elements constructed with digital fabrication techniques. *Int. J. Life Cycle Assess.* **2019**, *24*, 1027–1039. [CrossRef]
193. Jipa, A.; Bernhard, M.; Dillenburger, B.; Meibodi, M.; Aghaei-Meibodi, M. 3D-Printed Stay-in-Place Formwork for Topologically Optimized Concrete Slabs. In Proceedings of the 2016 TxA Emerging Design + Technology, San Antonio, TX, USA, 3–4 November 2016; pp. 1–11. [CrossRef]
194. Ali, E. Cradle to Gate Life Cycle Assessment (LCA) of 3D Printing Houses. *J. Earth Sci. Eng.* **2021**, *9*, 13–19. [CrossRef]
195. Mahadevan, M.; Francis, A.; Thomas, A. A simulation-based investigation of sustainability aspects of 3D printed structures. *J. Build. Eng.* **2020**, *32*, 101735. [CrossRef]
196. Zeng, Q.; Mao, T.; Li, H.; Peng, Y. Thermally insulating lightweight cement-based composites incorporating glass beads and nano-silica aerogels for sustainably energy-saving buildings. *Energy Build.* **2018**, *174*, 97–110. [CrossRef]
197. Yang, S.; Wi, S.; Park, J.H.; Cho, H.M.; Kim, S. Novel proposal to overcome insulation limitations due to nonlinear structures using 3D printing: Hybrid heat-storage system. *Energy Build.* **2019**, *197*, 177–187. [CrossRef]
198. He, Y.; Zhang, Y.; Zhang, C.; Zhou, H. Energy-saving potential of 3D printed concrete building with integrated living wall. *Energy Build.* **2020**, *222*, 110110. [CrossRef]