sustainability

MDPI

Article

Assessing the Prospects and Risks of Delivering Sustainable Urban Development Through 3D Concrete Printing Implementation

Liubov Adamtsevich *, Andrey Pustovgar and Aleksey Adamtsevich

Scientific Research Institute of Construction Materials and Technologies, National Research Moscow State University of Civil Engineering, 26 Yaroslavskoye Shosse, 129337 Moscow, Russia
* Correspondence: shilovala@mgsu.ru

Abstract: The article presents the results of a comprehensive study of the use of 3D Concrete printing (3DCP) technology to create urban infrastructure facilities according to sustainable development principles. The work includes a study of scientific articles on the subject area under consideration, a survey of additive construction market participants, as well as an analysis and generalization of promising areas for technology development and methods for improving the quality of objects erected using 3DCP. As part of the conducted literature review, publications included in the Scopus database for the period 2015–2024 were selected for analysis using the keywords 'Sustainable development + 3DCP' and 'Sustainable construction + 3DCP'. The following conclusions were made: (i) the most popular publications are review articles about the development of materials and technologies for 3DCP and (ii) the most sought-after are the studies in the field of partial application of 3DCP technology, existing equipment and materials for 3DCP, and assessment of the effectiveness and cost-effectiveness of 3DCP use. For this purpose, a questionnaire was developed consisting of three blocks: equipment and technologies; structures and materials for 3DCP; the ecology and economics of 3DCP applicability. As a result, four main risks have been identified, which represent promising areas for 3DCP development.

Keywords: 3DCP; additive manufacturing; sustainable development; Industry 4.0; 3D concrete printing

check for updates

Citation: Adamtsevich, L.; Pustovgar, A.; Adamtsevich, A. Assessing the Prospects and Risks of Delivering Sustainable Urban Development Through 3D Concrete Printing Implementation. *Sustainability* **2024**, *16*, 9305. https://doi.org/10.3390/su16219305

Received: 8 September 2024
Revised: 13 October 2024
Accepted: 23 October 2024
Published: 26 October 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The active development of humankind is inextricably linked to the consumption of resources, not only for subsistence itself, but also for the production of tangible and intangible goods. Over time, the world's population has grown and resources have been depleted, providing the starting point for the development of solutions to protect the environment from excessive anthropogenic impact.

By the end of the 1960s, the issue of increasing environmental tensions had become acute. Since then, scientists around the world have been trying to develop methods and algorithms to identify and calculate trends in socio-economic development, considering possible environmental impacts. It was during this period that the foundations for the concept of sustainable development were laid.

In the mid-twentieth century, the term 'sustainable development' began to be used for fishery resources in Canada, as well as forest resources in Germany, but even then, the common ground was that resource exploitation should not exceed natural growth.

The next stage in the development of the concept of 'sustainable development' can be considered the emergence of such theories as 'limits to growth' and 'sustainable growth', which confirmed the hypothesis that the implementation of the policy of 'sustainable growth' is inextricably linked to the formation of a 'sustainable society'. This direction was first described in the work of L. Brown in 1981 "Building a sustainable society". This work is considered to be the beginning of the dissemination of research in this area in the

academic environment and the commencement of growth in the number of publications attributed to this issue, which is confirmed by statistical data on the dynamics of changes in the number of publications in the Scopus database, collected by the keyword 'sustainability' (Figure 1).

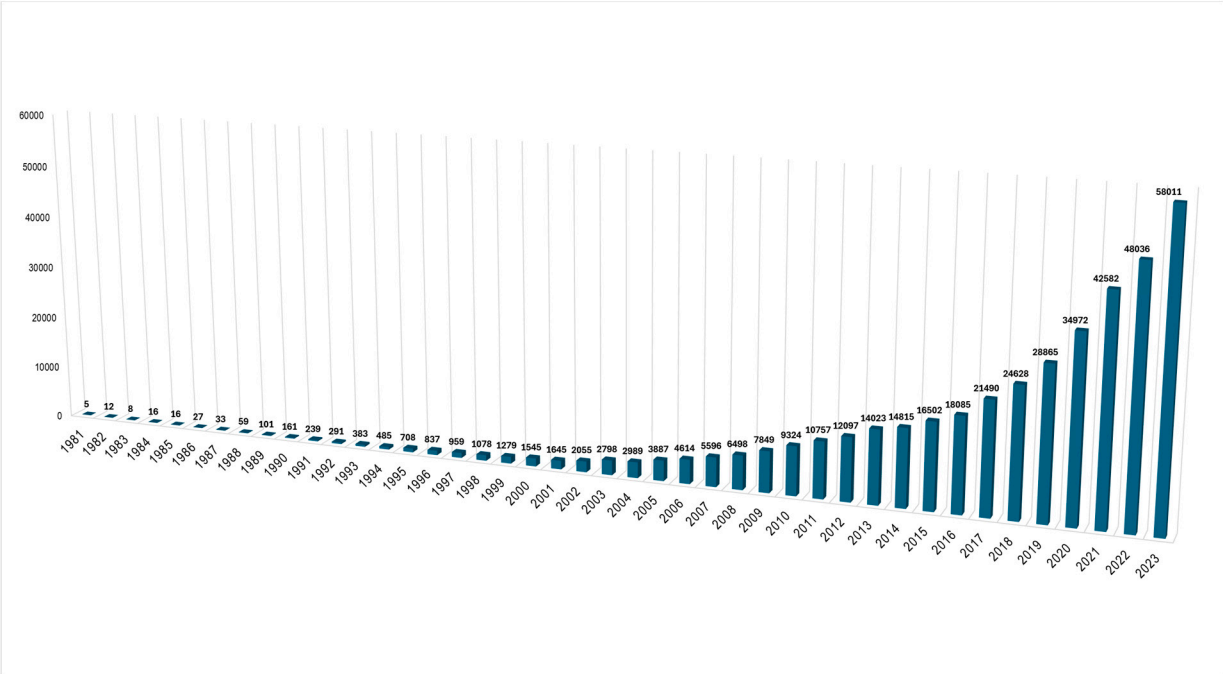


Figure 1. Dynamics of changes in the number of publications recovered using the keyword 'sustainability' in the Scopus database for the period from 1981 to 2023.

Moreover, approximately 62% of all publications come from 15 countries (Figure 2), where the top three at the time of writing of this study were the United States of America (12.6%), Great Britain (6.72%) and China (6.71%).

The most popular fields of knowledge to which publications relate are environmental science—155,793 (17.0%), the social sciences—131,296 (14.3%) and engineering—105,844 (11.5%), i.e., totaling about 42.8%, which indicates that sustainable development is achieved, as a rule, through the development of environmentally friendly engineering solutions for humanity. At the same time, in 1980, as part of the report "World Conservation Strategy" at the congress of the International Union for Conservation of Nature and Natural Resources, it was announced that to ensure sustainable development, it is necessary to consider not only the economic but also the social and environmental aspects of human development. In the sense in which it is used today, the term "sustainable development" appeared in 1987, when the Report of the World Commission on Environment and Development "*Our Common Future*" presented a triune concept of sustainable development that includes the economic, social, and environmental aspects of human development.

In 2012, the Rio + 20 summit in Brazil decided to develop sustainable development goals, and in 2015, 193 countries agreed on 17 Sustainable Development Goals and committed to achieving them by 2030.

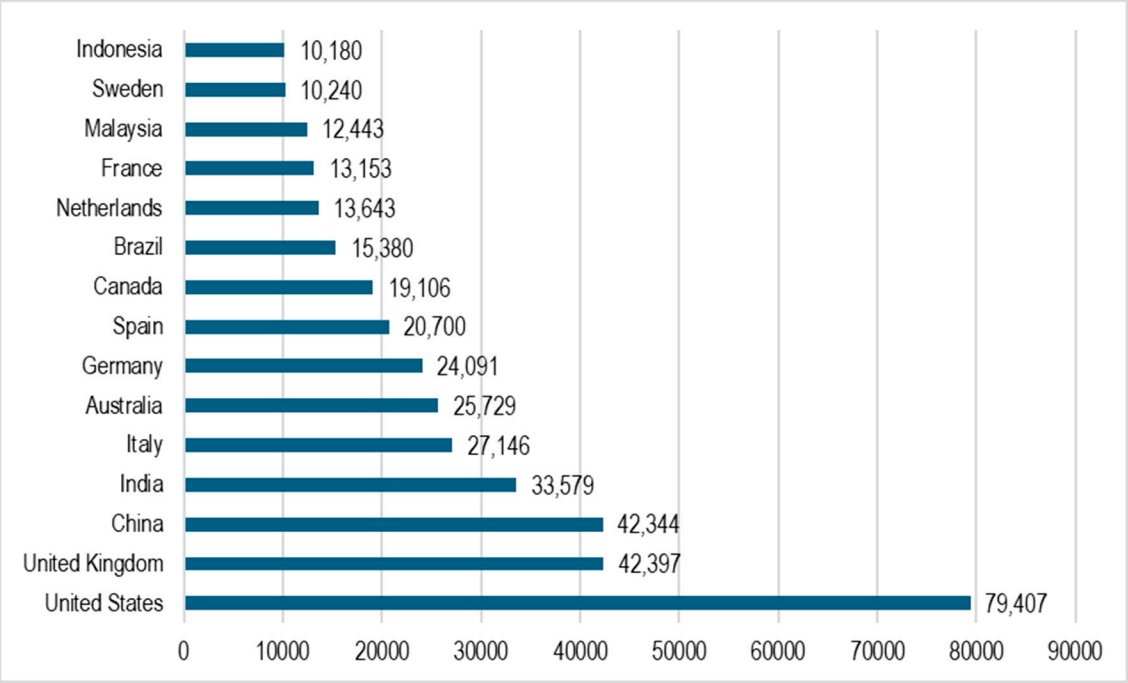


Figure 2. Distribution of publications by top 15 countries.

The 11th goal is to make cities and communities inclusive, safe, sustainable and environmentally friendly, i.e., to ensure sustainable urban development.

In this article, the authors put forward a hypothesis about the possibility of ensuring sustainable urban development by introducing 3D concrete printing (3DCP) technology using local materials and materials from recycled resources.

At the same time, there are already a number of publications confirming the relationship between concrete printing (3DCP) and sustainable urban development.

For instance, there are potential benefits, such as reducing material waste [1,2], ensuring sustainable construction [3], increasing construction speed [1,2,4] and lowering carbon emissions [5–9].

In addition to the above, the authors [1] also identified such advantages as:

- ✓ Lower resource consumption;
- ✓ The construction process is safe, clean and accurate;
- ✓ Free design, light weight, high strength and multifunction;
- ✓ Highly customizable, including the possibility of standardizing and personalizing decisions.

One work [3] emphasizes that additive manufacturing or 3D concrete printing provides a complete digital solution to conventional construction practices and fosters sustainable, smart and green building concepts.

The experiment conducted by the authors of [4] showed that productivity had improved by 50% compared to the original conventional methods.

Also, 3DCP directly addresses urban infrastructure challenges [10–13].

It should be mentioned that 3DCP technology helps to develop urban infrastructure by offering new opportunities to create sustainable, efficient and esthetically pleasing solutions.

There are already examples of bridges being built using 3D printing. This method was successfully applied to the Striatus pedestrian bridge in Venice, which was the first 3D-printed concrete bridge of its kind.

A smaller and improved version of the Striatus bridge, the Phoenix pedestrian bridge, was designed by the department Zaha Hadid Architects, specializing in digital design, and a research team from the higher technical school ETH Zürich, which is dedicated to finding

new expressive forms in construction. The world's largest 3D-printed concrete pedestrian bridge has appeared over a pond in Shanghai's Baoshan neighborhood.

It is also worth noting such positive aspects of the application of this technology as the shortening of construction time. This aspect is especially relevant when mitigating the consequences of emergencies.

Sustainable urban development also contributes to reducing material costs through the use of recycled materials, as well as cutting labor costs.

At the same time, the active development of technology is impossible without certain difficulties. This study's goal is to identify issues that are poorly understood and require additional research.

2. Materials and Methods

2.1. Development of Questionnaires

Figure 3 shows the stages of the study. The color identifies stages that belong to the same block but include a more detailed description of the stage.

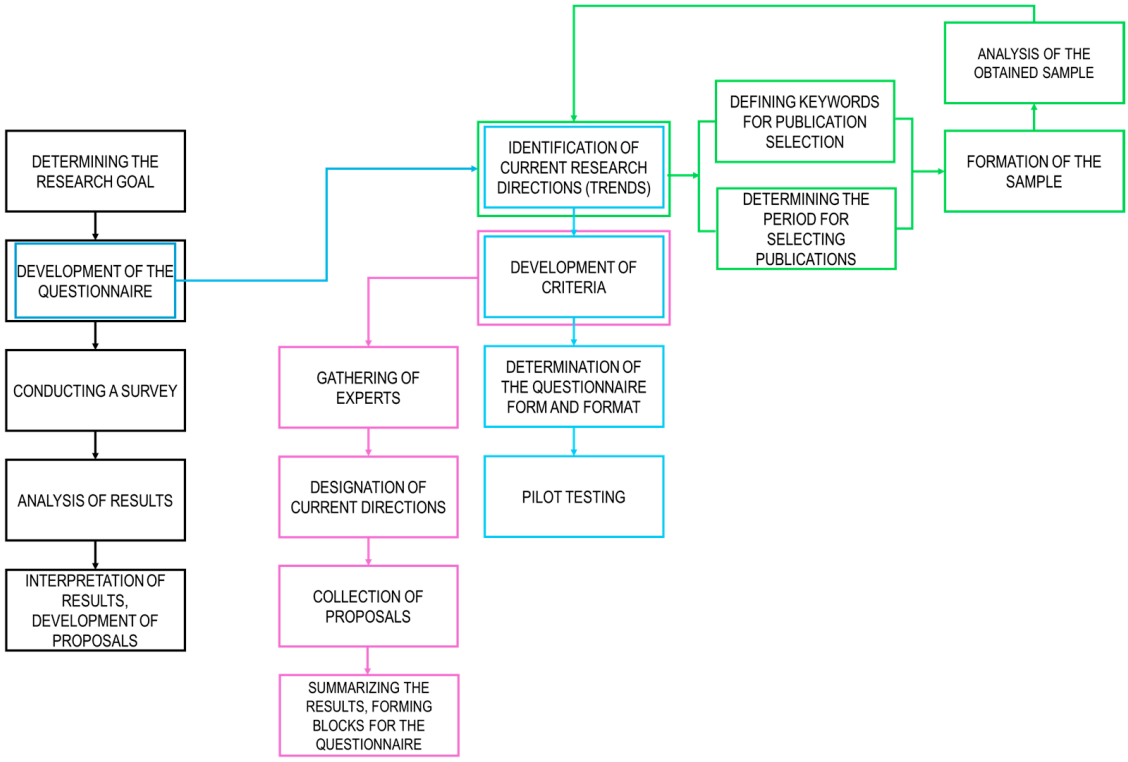


Figure 3. Detailed research scheme.

At the first stage of the study, a selection of publications presented in Scopus using the keyword phrase 'sustainable cities and communities' was generated to identify promising areas for research in this field.

The period of publication is constrained to the period from 2015 to 2024, since this goal was adopted and approved in 2015, and a total of 8873 documents are displayed in the sample. The analysis of the sample revealed that promising technologies within the framework of this area are currently technologies of Industry 4.0 such as the smart city (880); IoT (146); artificial intelligence (102); machine learning (86), while the technology of 3D concrete printing or additive construction also refers to the technologies of Industry 4.0, but currently remains little studied in terms of justifying its applicability for achieving the goals of sustainable urban development.

At the next stage, to form a real picture of the use of technology within the framework of ensuring sustainable development, two samples were formed by keywords:

✓ Sustainable development + 3d concrete printing (3DCP) (sample 1);
✓ Sustainable construction + 3d concrete printing (3DCP) (sample 2).

The display period is taken the same as in the first case—from 2015 to 2024. Figure 4 shows the dynamics of changes in the number of publications by year, by keywords, and Figure 5—the top 10 leading countries. At the same time, 41.1% of all publications in sample 1 relate to engineering, 20.9% to materials science and 7.3% to computer science; for sample two, the following distribution of the first three places are:

— engineering—38.5%;
— materials science—17.5%;
— environmental science—8.9%.

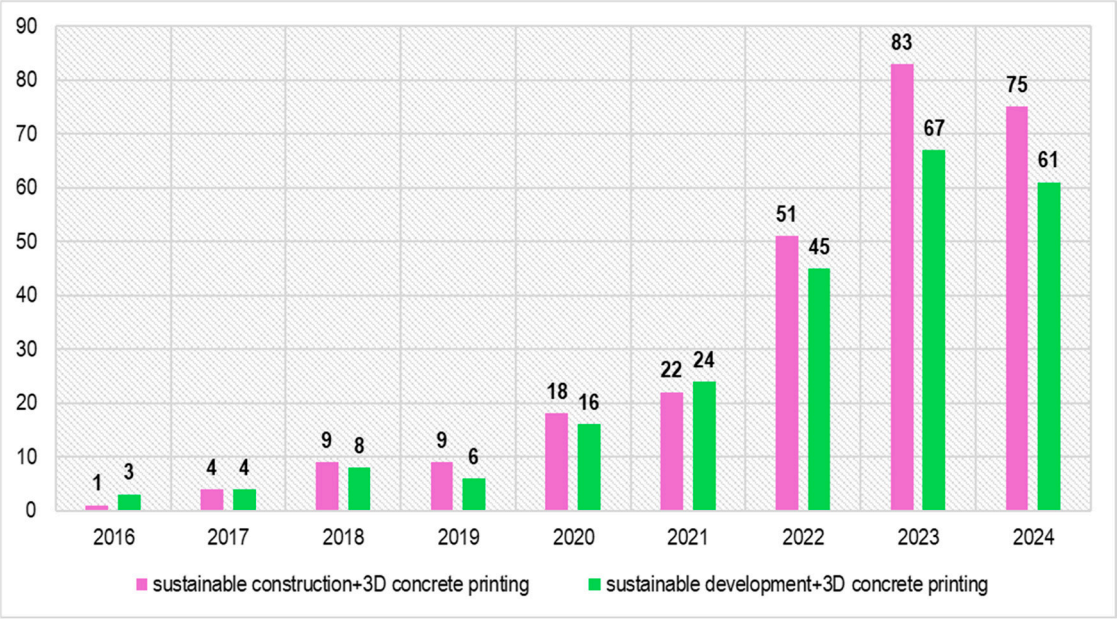


Figure 4. Dynamics of changes in the number of publications by year by keywords.

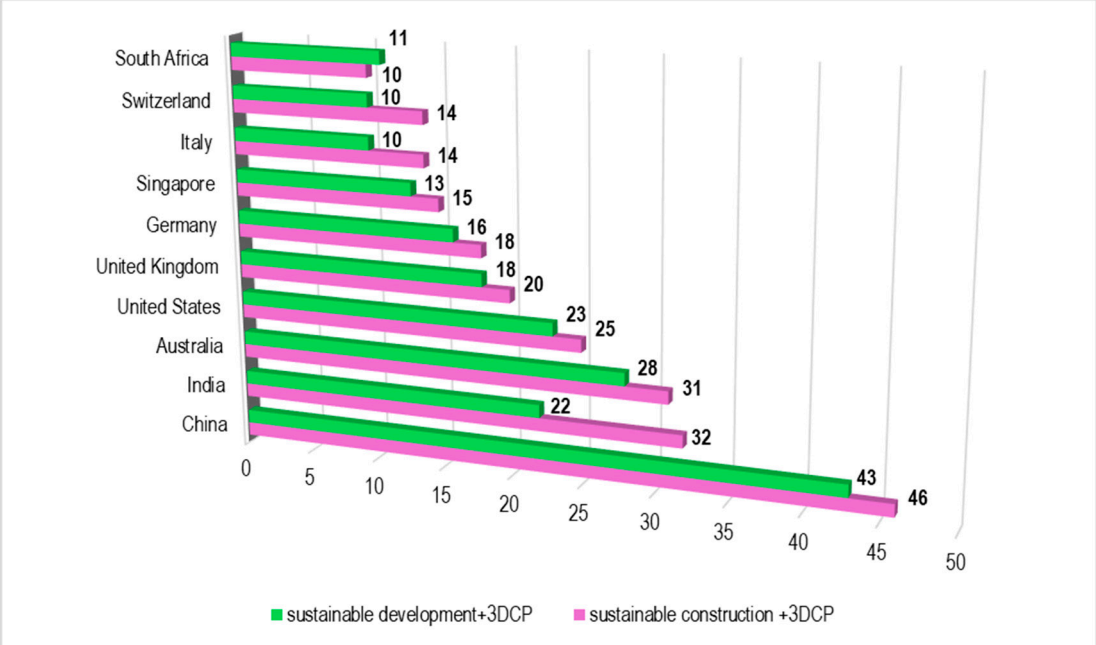


Figure 5. Top 10 countries—leaders in publications for selected keywords.

Based on the data obtained, it can be concluded that the number of publications recovered using the specified keywords is growing, but they are still few in number, with the leaders being authors from such countries as China, India, Australia and the USA. To identify the main problems and challenges on the path to the active implementation of this technology for sustainable urban development, the next stage was to analyze the most cited publications. The sample included articles with 40 or more citations. Table 1 presents a summary of the most cited publications, highlighting the main direction of the study. A total of 50 publications were selected that met the selected constraints.

Table 1. A summary of the most cited publications in Scopus, highlighting the main direction of the research.

Link	Summary	Number of Citations	Problems
[14]	The article presents the results of experimental studies on reinforcement with short glass fiber of different lengths (3 mm, 6 mm and 8 mm) and percentage content (0.25–1%) of the material developed for 3D printing. The experimental results revealed an improvement in the properties of printed samples with an increase in the percentage of fibers to 1% and an obvious directional dependence of behavior.	462	Materials/constructions
[15]	The article presents the current state of research in the field of 3D printing of buildings and their components. The conducted research identified Contour Crafting as the most promising technology	382	Review article
[16]	This article evaluates the potential of fly ash-based geopolymer cement for large-scale additive manufacturing of structural components.	361	Materials
[17]	The study presents the development of fly ash-based geopolymer mixtures for 3D concrete printing.	307	Materials
[18]	The article is devoted to a review of the applicability of concrete as a promising material for ensuring the sustainability of construction.	244	Review article
[19]	The article examines the current state of research in the field of 3D concrete printing using cement composites to identify the most promising areas of research.	196	Review article
[20]	The article presents the results of the research on the transformational changes in the construction industry. It is noted that the following technologies will be of decisive importance in the construction of cement and concrete: (i) additive manufacturing, (ii) additives, (iii) managed material data warehouses, (iv) composites designed using computation, (v) big data and intelligent materials, (vi) alternative binder compositions and (vii) next-generation devices.	187	Review article
[21]	The article presents the results of studies on the effect of a viscosity modifier based on hydroxypropyl methylcellulose on the suitability for use in 3D printing and mechanical characteristics of a cementitious material based on limestone and calcined clay.	174	Materials
[22]	The article is devoted to the environmental and economic assessment of 3D-printed buildings using material based on recycled concrete.	168	Ecology

Table 1. *Cont.*

Link	Summary	Number of Citations	Problems
[23]	The article presents the results of an economic, environmental and performance evaluation of a concrete bathroom manufactured using 3D printing and precast concrete. The study assessed the material consumption, energy costs, labor costs/productivity and installation cycle. The results show that the bathroom manufactured using 3DCP achieves a 25.4% reduction in total cost, 85.9% reduction in CO_2 emissions and 87.1% reduction in energy consumption compared to precast concrete.	160	Ecology, economics
[24]	The article provides a comprehensive overview of eco-friendly materials for 3D concrete printing.	141	Review article
[25]	The article presents the results of research on the environmental assessment of large-scale construction using 3D printing in comparison with traditional construction methods and two types of building materials: concrete and adobe.	126	Ecology
[26]	The review presents the latest advances in the application of the fused deposition method in 3D printing using biomaterials. In particular, the properties and characteristics of biopolymers, their composites and polymers containing biofillers are discussed.	108	Review article
[27]	The article discusses the possibility of using microwave heating to increase the rate of structuring of geopolymer concrete in the context of 3DCP application.	101	Technology
[28]	This article presents a systematic review of current research on the application of 3D concrete printing technology as a promising method for sustainable construction in terms of reducing or eliminating the energy and environmental footprint, as well as its socio-economic impact.	99	Review article
[29]	This article presents an overview of the use of industrial waste in 3D concrete printing processes. The article highlights the positive impact of using industrial waste in increasing the sustainability of 3D-printed structures.	98	Review article
[30]	The article focuses on the possibility of using geopolymers for 3D printing. The optimal mixture for geopolymers cured at ambient temperature is determined.	98	Materials
[31]	The aim of this article is to improve the printability and mechanical properties of a "one-component" geopolymer for 3D concrete printing (3DCP).	95	Materials
[32]	This article presents a study of sustainable limestone and calcined clay-based cementitious materials for 3D concrete printing, investigating the effect of different calcined clay grades on extrudability and early strength development under environmental conditions.	95	Materials
[33]	The article discusses the properties of geopolymer concrete, as well as the factors that influence these properties. Technological schemes are proposed that show which factors have a greater/lesser influence on the properties of fresh and hardened geopolymer concrete.	84	Review article
[34]	This article examines the environmental trade-offs of using 3DCP compared to traditional construction by conducting a detailed life cycle assessment study.	79	Ecology

Table 1. *Cont.*

Link	Summary	Number of Citations	Problems
[35]	This article provides an overview of 3D concrete printing processes and their potential in the construction industry.	78	Review article
[36]	The study presents a robotic process for manufacturing custom concrete structures.	76	Technology/equipment
[37]	The article presents the results of research on the use of antimony tailings in fiber-reinforced concrete for the implementation of 3D concrete printing technology. Antimony tailings increase the durability and strength of the material, while promoting sustainability by reducing waste, which provides a cost-effective and environmentally friendly solution for construction.	71	Materials
[38]	This article presents a systematic review of the current state of the art of five different 3D printing technologies currently used for formwork manufacturing.	71	Review article
[39]	This article provides a critical review of the current state of the art of 3D printing geopolymers in terms of manufacturing process, printability requirements, mix design, early material properties and sustainability.	69	Review article
[40]	The article presents the results of studies on the influence of materials used in 3DPC mixtures on the printing characteristics of mixtures, especially rheological properties, based on current publications.	66	Review article
[41]	This article provides a comprehensive overview of current trends and opportunities for sustainable concrete construction, highlighting the importance of adopting environmentally friendly practices to mitigate the industry's environmental impact.	59	Review article
[42]	This article provides a comprehensive review of the current state of the art of geopolymer composites in terms of mix design, fabrication process, engineering properties, durability and environmental benefits.	58	Review article
[43]	This article presents a literature review on the use of cementitious materials for 3D printing in the context of environmental sustainability.	56	Review article
[44]	The article presents the results of a comprehensive review of 3D printing, performance requirements, advantages, disadvantages and common technologies.	55	Review article
[45]	The study designed a two-story building using five different construction methods: 3DCP, precast modular construction, cast-in-place reinforced concrete, cold-formed steel and hot-rolled steel. The study found that, except for precast modular concrete, 3DCP reduced construction time by approximately 95%. The use of 3DCP also provided the greatest cost savings and performed similarly to cold-formed steel, producing approximately 32% less CO_2 emissions.	55	Economics
[46]	The article presents an overview of the applicability of wood powder as a component of 3D printing, an analysis of the properties of the resulting products and an assessment of the potential for the applicability of the material in the future.	53	Review article

Table 1. *Cont.*

Link	Summary	Number of Citations	Problems
[47]	The article analyzes the current development of additive manufacturing technologies using geopolymers as promising environmentally friendly and sustainable aluminosilicate inorganic materials for 3D printing.	52	Review article
[48]	The study describes the potential applications of magnesium oxide-based reactive cement using 3D printing technology.	52	Materials
[49]	This article provides a comprehensive overview of research trends, open issues and key performance indicators of the application of mobile robots in additive manufacturing.	51	Review article
[50]	The article presents the results of research on the application of 3D printing based on 20 interviews with specialists from Central and Northern Europe who are pioneers in the implementation of 3DCP technology. The main trade-offs in sustainability issues in the implementation of 3D concrete printing in the construction industry are identified.	51	Technology
[51]	The article presents the results of research into the reinforcement of 3D-printed structures with plastic scaffolding.	50	Constructions
[52]	The article presents a relationship that provides insight into the environmental impact of 3D-printed structures and notes that form efficiency is the only unique benefit that digital concrete brings.	50	Ecology
[53]	The review presents the prospect of using various green cement materials, structural optimization applications and modularization methods to realize sustainable construction using additive manufacturing.	47	Review article
[54]	The article presents the main trends in the field of 3DCP application and provides an in-depth review of the properties of alkali-activated concrete composites used in 3D printing construction.	47	Review article
[5]	The article presents the results of a study on the possibility of using alkali-activated brick waste powder as a binder for the development of geopolymer mixtures for 3D printing.	46	Materials, ecology
[55]	This article provides a comprehensive overview of 3D concrete printing technology, as well as various materials, methods and application trends.	46	Review article
[56]	The article presents a new slab system that reduces material consumption by concentrating concrete in hierarchical ribs on a 20 mm thick concrete shell. The slab is made from prestressed concrete elements, for which the authors present a hybrid formwork approach combining 3D printing and CNC laser cutting of timber formwork. The Smart Slab is approximately 70% lighter than a conventional concrete slab and demonstrates the potential of 3D printing for customized formwork, especially when strategically combined with other CNC fabrication methods.	45	Constructions

Table 1. *Cont.*

Link	Summary	Number of Citations	Problems
[57]	The article examines experimentally determined material properties of four different printed foam concretes with densities ranging from 800 kg/m³ to 1200 kg/m³	44	Materials
[58]	The article presents the results of research to assess the environmental and economic efficiency of using 3D printing technology compared to traditional construction methods in large-scale structural fabrication.	42	Ecology, economics
[59]	The study presents a slag-based mixture as a cement-free 3D printing material.	41	Materials
[60]	The main aim of this article is to present sustainable performance criteria for 3D printing methods. The potential benefits of 3D printing include a reduction in construction waste due to high-precision material placement and the use of recycled waste in cladding materials. The authors developed a numerical model for 3D printing using a cementitious mixture including recycled high-density polyethylene. It was found that the construction of an arched roof in the form of a truss was structurally feasible without the use of steel reinforcement.	41	Materials/constructions
[61]	The article presents the results of developing an environmentally friendly 3D-printed ultra-high-performance fiber-reinforced concrete by replacing a large volume of the cement component of the mixture with fly ash and/or ground granulated blast furnace slag.	41	Materials
[62]	This article presents a study to quantify and understand the effects of the partial replacement of fly ash, metakaolin, kaolin, red mud, slag, ordinary Portland cement and silica fume on the setting time, workability, compressive strength and flexural strength of various raw materials discussed in published papers.	41	Materials

According to the analysis of publications the following conclusions can be drawn:

1. The most popular publications are review articles that examine current achievements in both the development of materials for 3D printing and the development of various approaches, including automated ones, for 3D printing;
2. The most in-demand studies are in the following areas:
   - o Technology for using 3D concrete printing;
   - o Existing equipment for 3D concrete printing;
   - o Materials for 3D concrete printing;
   - o Assessment of the environmental and economic efficiency of using 3D concrete printing.

Thus, it was decided to include the following blocks in the questionnaire:

- o Equipment and technologies;
- o Designs and materials for 3D concrete printing;
- o The ecology and economics of the applicability of 3D concrete printing technology;
- o Comments and suggestions.

Thus, the blocks for the questionnaire were defined. Further, at the meeting of Working Group No. 16 'Additive technologies in construction' FAU FCC under the Ministry of Construction and Housing and Communal Services of the Russian Federation, a discussion of the potential risks included in the thematic blocks was held.

Those risks that received the majority of votes of Working Group No. 16 'Additive technologies in construction' were included in the top nine risks of the thematic blocks.

Pilot testing was conducted on employees of the Research and Development Institute of Construction Materials and Technologies. As part of this stage, the final wording of the criteria was edited.

Figure 6 shows the final developed questionnaire "Assessment of the prospects and risks of developing additive construction production" for the "equipment and technologies" block, Figure 7—for the "materials and structures" block and Figure 8—for the "economy and ecology" block.

2.2. Rules for Filling Out Questionnaires

The items presented in the questionnaire must be ranked from 1 to N. If the participant did not add their criterion, then N = 9; if the participant thought an item was left out and added their own, then N = 10.

The most important criterion—the most critical risk—had to be assigned a rank of 1, the least important—N.

In the case when the expert considered the criterion unimportant, he could assign it a value of 0 or cross it out.

Thus, the output is a table of ranked risks that, in the opinion of the experts, hinder the development of 3DPC. Accordingly, these are the issues that should be paid attention to when conducting scientific research.

№	Criterion	Rating
1	High dependence on the construction region	
2	High cost of operation and maintenance of equipment for construction 3D printing	
3	High labor intensity and cost of installation and dismantling of a construction 3D printer, as well as its delivery to the construction site (low mobility)	
4	Insufficient functionality of the equipment available on the market for construction 3D printing	
5	Unavailability, low availability and/or too high cost of equipment for 3DCP	
6	Restrictions on the number of storeys of constructed buildings	
7	Lack of possibility to print horizontal (span) structures	
8	Lack of available software for creating G-code models and controlling construction 3D printers and/or low functionality of such software	
9	The need of using additional structures to protect against precipitation, wind and/or temperature changes at the construction site when using 3DCP technology	
10	Own answer	

Figure 6. "Equipment and Technology" Block.

№	Criterion	Rating
1	The impossibility of obtaining satisfactory surface quality for products and structures created using 3DCP technology	
2	Insufficient study of the influence of different extrusion modes on the final properties of printed products and structures	
3	Insufficient study of the issue of durability of structures erected using 3DCP technology	
4	Low adhesion between the layers being formed and/or the formation of "cold" joints in structures erected using 3DCP technology	
5	Difficulty in achieving expected and stable parameters of mechanical strength of structures erected using 3DCP technology, due to the impossibility of additional vibration compaction (or for other reasons)	
6	Difficulty in ensuring the ability to build up the 3DCP material during 3D printing (crushing of lower layers, loss of stability during the extrusion process)	
7	Difficulty in ensuring the ability to pump the material for 3DCP in the state of a mobile mixture with the rheological properties required for printing (mixture stratification, clogging of hoses)	
8	The complexity of designing and calculating buildings, structures and constructions of irregular geometric shapes, as well as variable cross-sections	
9	The complexity of designing material compositions with specified properties for 3DCP	
10	Own answer	

Figure 7. "Materials and Structures" Block.

№	Criterion	Rating
1	The need for a significant amount of electricity during implementing 3DCP technology.	
2	Little number of studies of using waste from 3DCP technology, including defective designs.	
3	Lack of standards for quality control of 3DCP, including environmental impact.	
4	Noise pollution from 3DCP technology	
5	Limited applicability of technologies in certain regions and countries of the world	
6	Job cuts	
7	Need for additional research on the application of 3DCP technology	
8	The need to attract highly qualified personnel	
9	Significant time expenditure on equipment setup and mixture development for a specific facility	
10	Own answer	

Figure 8. "Economy and Ecology" Block.

2.3. Participants of the Experiment

Specialists from manufacturing companies and research and educational organizations from China, India and Russia were invited to participate in the survey. According to [https://ourworldindata.org/grapher/annual-co2-cement] (accessed on 20 October 2024) and [Global Carbon Budget (2023) https://essd.copernicus.org/ (accessed on 20 October 2024], these countries together generate about 60% of all global CO_2 emissions from cement production (Figure 9), so the pace of their transition to less material-intensive construction technologies using concrete has a high impact on the sustainability of the entire global construction industry.

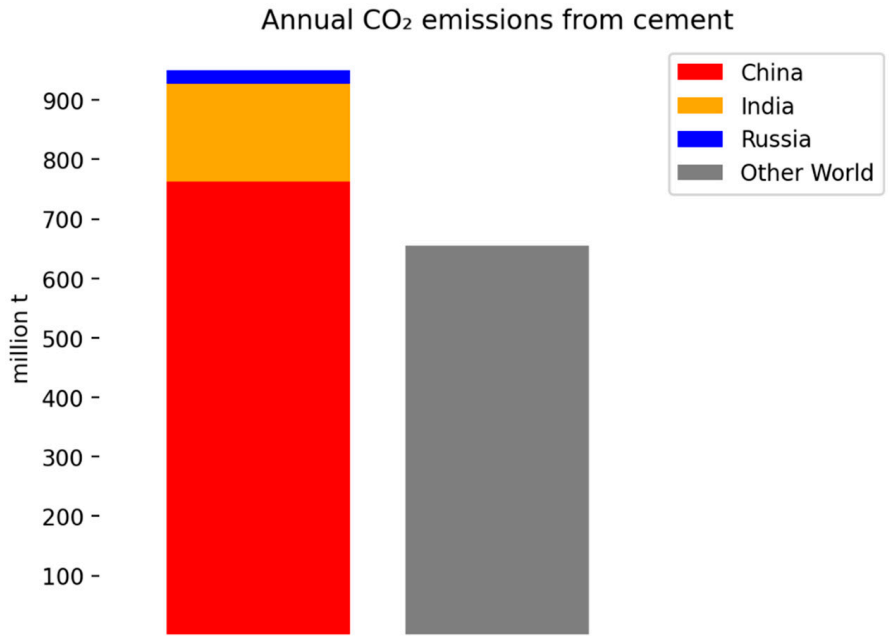


Figure 9. Contribution of countries to CO_2 emissions from cement production (based on 2022 data).

Another factor worth paying attention to: currently, the leaders in terms of sustainable construction are European countries such as the Netherlands, Belgium, Germany and others. However, when conducting research on the implementation of 3DCP in Europe, the focus is on environmental friendliness and economic efficiency [57,63,64], and in India and China—on economic development and innovation [65], in Russia—on innovation and technology. It is relevant to conduct research in countries with similar trends.

The survey involved representatives of the construction and design sphere, specialists in the production of dry construction mixtures, as well as representatives of scientific and educational organizations from Russia, China and India. The survey was conducted by filling out questionnaires on paper and via online electronic forms.

When conducting the questionnaire survey, the main criterion was the representativeness of the sample of experts involved, as an important factor is the correspondence of respondents to the key parameters of the general population.

In total, over 60 questionnaires were collected, with 67% of the survey participants being men and 33% being women; their distribution by organization is presented in Figure 10, and the distribution of organizations by areas of activity is presented in Figure 11.

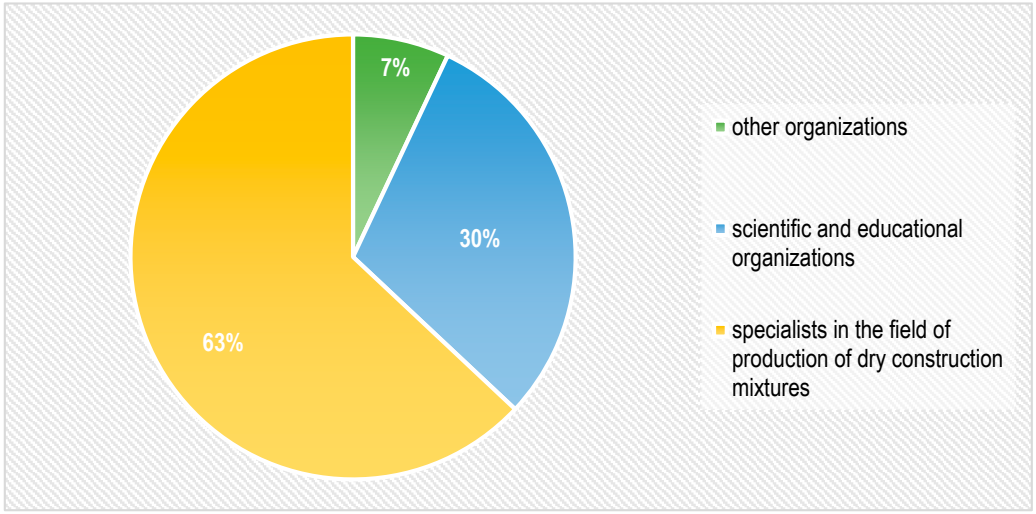


Figure 10. Specialists' distribution by organizations.

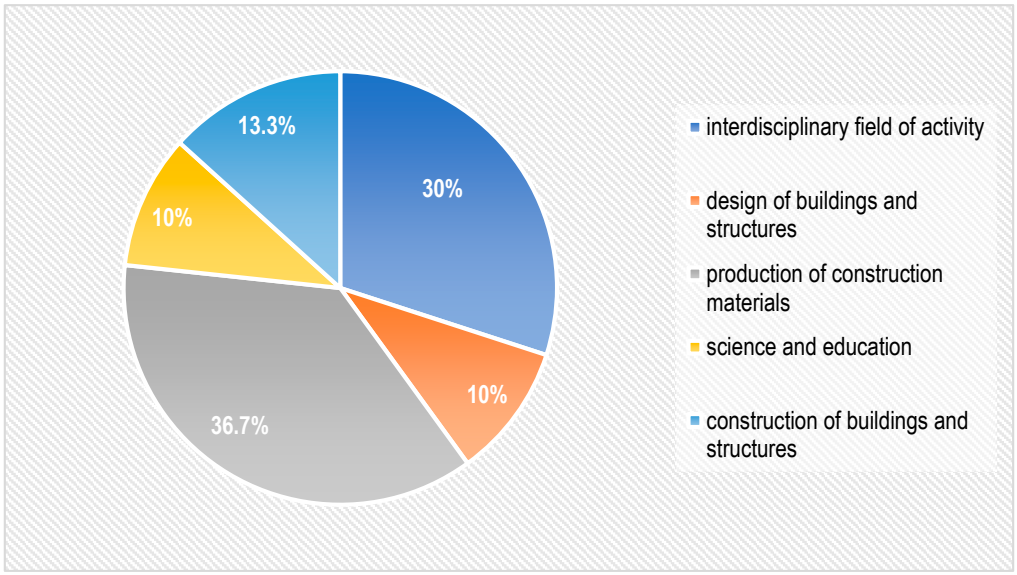


Figure 11. Distribution of organizations by areas of activity.

The survey results revealed that 35% of the respondents have practical experience working with 3DCP technology.

3. Results

The ranking of criteria by blocks, formed based on the results of the survey, is presented in Figures 12–14.

№	Criterion
1	Lack of possibility to print horizontal (span) structures
2	High dependence on the construction region
3	High cost of operation and maintenance of equipment for construction 3D printing
4	High labor intensity and cost of installation and dismantling of a construction 3D printer, as well as its delivery to the construction site (low mobility)
5	Insufficient functionality of the equipment available on the market for construction 3D printing
6	Unavailability, low availability and/or too high cost of equipment for 3DCP
7	Lack of available software for creating G-code models and controlling construction 3D printers and/or low functionality of such software
8	Restrictions on the number of storeys of constructed buildings
9	The need of using additional structures to protect against precipitation, wind and/or temperature changes at the construction site when using 3DCP technology

Figure 12. Ranking of "Equipment and Technology" criteria according to the obtained results.

№	Criterion
1	Insufficient study of the issue of durability of structures erected using 3DCP technology
2	The impossibility of obtaining satisfactory surface quality for products and structures created using 3DCP technology
3	Low adhesion between the layers being formed and/or the formation of "cold" joints in structures erected using 3DCP technology
4	Difficulty in achieving expected and stable parameters of mechanical strength of structures erected using 3DCP technology, due to the impossibility of additional vibration compaction (or for other reasons)
5	Difficulty in ensuring the ability to build up the 3DCP material during 3D printing (crushing of lower layers, loss of stability during the extrusion process)
6	Insufficient study of the influence of different extrusion modes on the final properties of printed products and structures
7	Difficulty in ensuring the ability to pump the material for 3DCP in the state of a mobile mixture with the rheological properties required for printing (mixture stratification, clogging of hoses)
8	The complexity of designing material compositions with specified properties for 3DCP
9	The complexity of designing and calculating buildings, structures and constructions of irregular geometric shapes, as well as variable cross-sections

Figure 13. Ranking of "Materials and Structures" criteria according to the obtained results.

№	Criterion
1	Need for additional research on the application of 3DCP technology
2	Lack of standards for quality control of 3DCP, including environmental impact.
3	Little number of studies of using waste from 3DCP technology, including defective designs.
4	The need to attract highly qualified personnel
5	Significant time expenditure on equipment setup and mixture development for a specific facility
6	Limited applicability of technologies in certain regions and countries of the world
7	Job cuts
8	Noise pollution from 3DCP technology
9	The need for a significant amount of electricity during implementing 3DCP technology.

Figure 14. Ranking of "Economy and Ecology" criteria according to the obtained results.

As a result of the conducted survey, 6.7% of respondents determined 3DCP to be an unpromising technology, 3.3% refrained from assessing the technology and 90% determined that the technology is promising. The key risk in the "equipment and technology" block was indicated by the respondents as being the lack of the possibility of printing horizontal (spanning) structures.

This problem leads to a limitation of possibilities for designers and architects, preventing them from creating complex shapes. It also causes the use of additional materials and increases the amount of waste in the construction process.

In the "Materials and structures" block, the first place is given to "Insufficient study of the issue of durability of structures erected using 3DCP technology", and the second place goes to the criterion "The impossibility of obtaining satisfactory surface quality for products and structures created using 3DCP technology"; however, the gap between these criteria is insignificant.

This can be justified by the fact that the durability and reliability of 3D-printed structures are critical parameters for the safety and sustainability of buildings. Therefore, the lack of durability data may cause doubts among potential customers and investors alike, leading to a decrease in confidence in the technology.

At the same time, assessing the durability and reliability of 3D-printed designs requires long-term research and testing, which can take considerable time and resources.

With regard to the second risk, "The impossibility of obtaining satisfactory surface quality for products and structures created using 3DCP technology", it is worth noting that a harmonious building façade creates an esthetic visual environment, which improves the overall perception and comfort of residents. Along with this, in terms of developing technology, the esthetic appearance of printed houses can obviously attract more potential investors, which will also contribute to the success and development of the technology itself.

In the "Ecology and Economics" block, the risk "Need for additional research on the application of 3DCP technology" leads with a significant gap.

The need for additional research is primarily related to the solving of technology standardization issues, i.e., the development of unified international standards for 3DCP.

In addition, the issues of the durability and stability of printed structures remain poorly studied, as does the need to develop methods for the use of recycled materials and waste reduction.

Thus, significant investments are required in the early stages of technology implementation, which determines the leading position of this risk.

Additional information separately determines such risks as the high cost of materials, the lack of targeted investment programs, the lack of a market for ready-made design solutions for buildings and structures using 3DCP technology and the small number of educational programs for training 3DCP personnel.

The respondents put the issues of materials development in first place, followed by the solution of design problems. In Russia, issues of regulatory and personnel support have also become relevant. In terms of regulatory support, the following issues have been raised:

- ✓ The inadequacy of regulatory and technical requirements for materials (mixtures) for additive construction, considering the purpose of the products, structures and objects being created;
- ✓ The inadequacy of the standardized testing methods necessary to confirm the quality of materials for 3DCP;
- ✓ The lack of standards and rules for organizing high-altitude work using 3DCP technology;
- ✓ The lack of regulatory requirements for the reinforcement of products and structures manufactured using 3DCP technology;
- ✓ The lack of standard design solutions and methodological recommendations for the design of structural units of buildings and structures erected using 3DCP technology;
- ✓ The lack of procedures and criteria for combining the technology of 3DCP with other building materials for various applications, including equipment requirements;
- ✓ The difficulty of successfully submitting design documentation for facilities with various purposes erected using 3DCP technology, due to the conservative attitude of experts;
- ✓ The difficulty of successfully submitting design documentation for facilities with various purposes erected using 3DCP technology, due to the non-compliance of the final product with the prescriptive requirements of existing regulatory documents (the presence of direct regulatory barriers);
- ✓ The complexity of developing design documentation for facilities constructed using 3DCP technology, due to the lack of design standards and methods for building structure analysis.

In terms of personnel policy:

- ✓ The shortage of qualified personnel for designing facilities for construction using 3DCP technology;
- ✓ The shortage of qualified personnel to work with ASP equipment.

4. Discussion

As a result of the study, the most characteristic risks were identified, the solutions to which should be addressed by representatives of different target groups of 3DCP industry participants:

- ✓ The lack of the possibility of printing horizontal (span) structures;
- ✓ The insufficient study of the issue of the durability of structures erected using 3DCP technology;
- ✓ The impossibility of obtaining a satisfactory surface quality for products and structures created using 3DCP technology;
- ✓ The need for additional research on the application of 3DCP technology.

In terms of comments and suggestions, the key, in the authors' opinion, is the proposal to develop the integration of the complex use of Industry 4.0 technologies to obtain a synergistic effect at the stage of the widespread introduction of additive technologies into construction practice. Among the additional potential risks of developing construction using 3D printing technology, which were not mentioned in the original questionnaire, many survey participants noted the need to develop mechanisms for managing the printing process to ensure the high stability of the quality of the finished structures based on artificial intelligence and the use of machine learning algorithms. A similar proposal in terms of meaning was raised by 63% of the respondents.

Research in this area is actively conducted in different countries, which is confirmed by existing publications. For example, it is noted in [66] that quality assessment of 3D-printed structures is important because the workability of concrete decreases with printing time. In [66], a quality assessment method based on computer vision using a two-component linear binary texture analysis is proposed. Information entropy is used as a metric to measure the texture variation in each layer, and its changes are studied layer by layer. At the same time, the threshold entropy value is calculated using the error minimization method, by which the printed texture can be evaluated and action can be taken.

The authors of the study also developed a machine vision model for determining the quality of printing which is trained using a database of photographs and labeled data sets of possible defects that can occur during the printing of elements and structures of different shapes, maintained in the laboratory of the Scientific Research Institute of Construction Materials and Technologies of Moscow State University of Civil Engineering (Figures 14 and 15).



(**a**) interior walls surface (**b**) façade surface

Figure 15. The house in the ecological park "Yasnoye Pole" printed on a 3D-printer. (**a**) Interior wall surfaces, (**b**) façade surface (source: authors' photo).

The algorithm starts by loading an image using the OpenCV image processing toolkit in Python 3.12. To simplify the process of structure contour detection, the image is pre-processed, including removing color information and converting it to grayscale to reduce the file size, then the image is blurred to reduce noise (Gaussian blur). After pre-processing, the canny edge detection algorithm is applied. This algorithm highlights the boundaries of objects in the image by selecting areas with large changes in pixel intensity.

Next, the contour search algorithm is applied to the processed boundaries. A contour is a curve that describes the boundary of an object. OpenCV 4.9.0 provides the findContours() function for this. The found contours are drawn onto the original image to visually indicate their position using the drawContours() function in OpenCV.

Printing process of one of the test samples at different time intervals is shown in Figure 16. Figure 17 shows the elements of the dataset. The simulation results are shown in Figure 18b, and Figure 18a shows the original image for analysis.

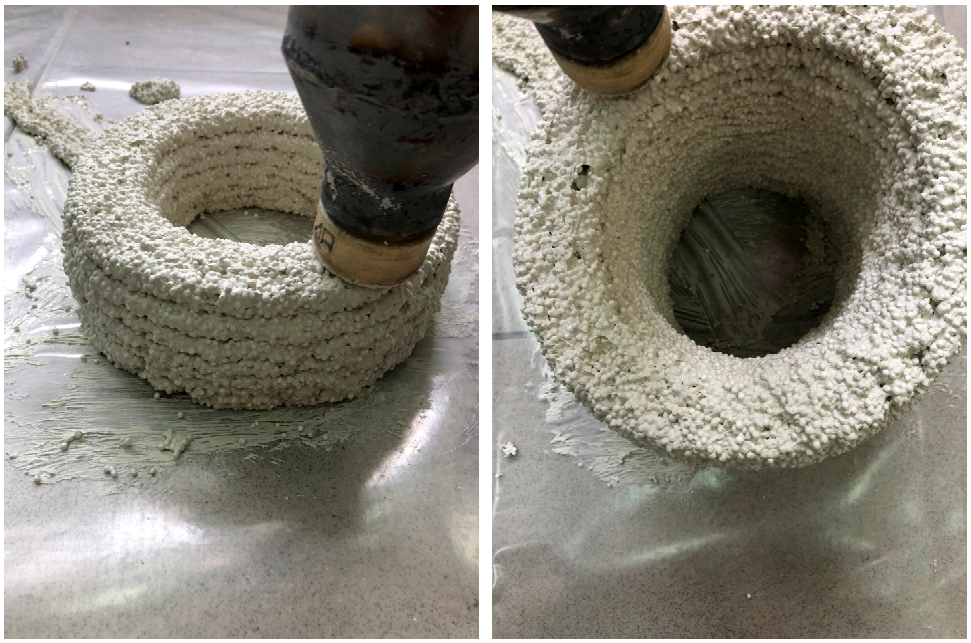
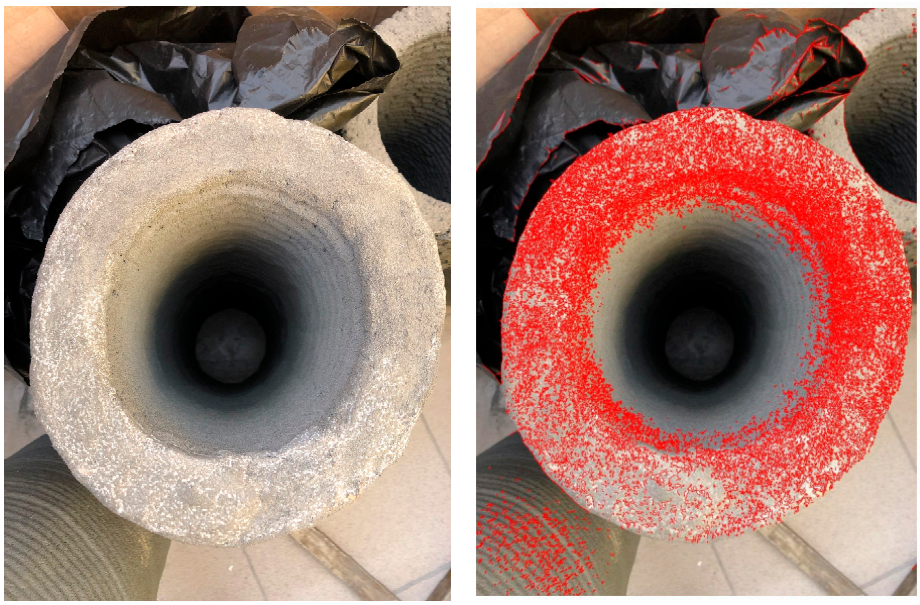


Figure 16. Printing process of one of the test samples at different time intervals. (**left**) at the beginning of the process, (**right**) top view of the construction at the end of the process.



Figure 17. The fragments of a graphic data array at the collection stage.



(**a**) (**b**)

Figure 18. The original photo (**a**) and the result of the quality control model (**b**).

5. Conclusions

The conducted research enabled us to form an assessment of the prospects and risks of 3DCP technology development and determine the order of problem solving to increase the pace of technological development, especially in the BRICS countries.

Four main risks were identified, which present promising areas for the development of 3DCP:

- ✓ The lack of the possibility of printing horizontal (span) structures;
- ✓ The insufficient study of the issue of the durability of structures erected using 3DCP technology;
- ✓ The impossibility of obtaining a satisfactory surface quality for products and structures created using 3DCP technology;
- ✓ The need for additional research on the application of 3DCP technology.

To reduce the impact of the above-mentioned risks on the development of 3DCP, a number of measures can be taken. The first is the development and introduction of international standards and certifications for 3DCP technology.

In order to standardize the development of 3D concrete printing, it is necessary to actively promote the international cooperation of scientific communities, and to ensure the active comprehensive implementation of Industry 4.0 technologies.

The development of these fields of study will help to elaborate international standards and norms for 3DCP, thus providing uniformity in the quality of products and facilitating international cooperation and exchange of experience.

Based on the existing experience of regional associations, the establishment of international associations and organizations whose mission is to support the development of technology is also seen as positive.

It is important to organize and hold specialized international conferences, seminars and forums to share knowledge and experience between specialists with expertise in 3DCP from different countries. Such events will allow for rapid dissemination of best practices and technologies.

Joint research projects between research institutes and technology companies from various countries will also accelerate technology development. In this direction, there are positive examples of joint RSK and DST projects realized in Russia and India, and RSF and NSFC in Russia and China, respectively.

Another important trend is the development and implementation of international training and certification programs for 3DCP specialists in order to upgrade the qualification level of specialists and standardize their skills and knowledge to ensure the satisfactory surface quality of articles and structures produced by means of 3DCP technology.

At the same time, the integrated use of technologies, such as the Internet of Things (IoT), big data and artificial intelligence (AI), to monitor and optimize 3DCP processes will make it possible to collect new data that can be used to improve process optimization and efficiency, which is also supported by the authors' of this study.

Future promising research on 3DCP applications should include a close look at the economic benefits that make 3D printing technology attractive to various industries, helping to cut costs, speed up production processes and enhance product quality.

Such areas could be:

- ✓ Reducing production costs by minimizing waste and optimizing production processes;
- ✓ Shortening development and production time through rapid prototyping and the possibility to create complex and unique elements;
- ✓ Cutting operation costs by selecting the optimal building shape and geometry to improve the energy efficiency of the facility and save energy used for the heating and cooling of buildings.

Also, important areas of focus are:

- ✓ The lack of clear design criteria for 3DCP technology;
- ✓ The risks and challenges of 3DCP technology for ecosystems;
- ✓ The risks and challenges of 3DCP technology for industry organizations.

In the framework of future research, the authors are planning to expand the geographical scope of the questionnaire in order to identify positive practices in European countries, with the purpose of their transfer and the adaptation of accumulated experience to the specific features of the countries under consideration.

Author Contributions: Conceptualization, L.A., A.P. and A.A.; methodology, L.A., A.P. and A.A.; validation, L.A., A.P. and A.A.; formal analysis, L.A.; investigation, L.A., A.P. and A.A.; resources, L.A. and A.A.; data curation, L.A. and A.A.; writing—original draft preparation, L.A.; writing—review and editing, L.A., A.P. and A.A.; visualization, L.A. and A.A.; supervision, A.P.; project administration, A.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the National Research Moscow State University of Civil Engineering (grant for fundamental and applied scientific research, project No. 25-392/130).

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhu, B.; Pan, J.; Zhou, Z.; Zhang, Y. Advances in Large-scale Three-Dimensional Printing Technology Applied in Construction Industry. *Cailiao Daobao/Mater. Rev.* **2018**, *32*, 4150–4159. [CrossRef]
2. Ebrahimi, M.; Mohseni, M.; Aslani, A.; Zahedi, R. Investigation of thermal performance and life-cycle assessment of a 3D printed building. *Energy Build.* **2022**, *272*, 112341. [CrossRef]
3. Dey, D.; Srinivas, D.; Panda, B.; Sitharam, T.G. Processing of Cementitious Materials for 3D Concrete Printing. In *Lecture Notes in Mechanical Engineering*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 283–291. [CrossRef]
4. Oktaviani, A.D.; Berawi, M.A. Implementation of 3D Concrete Printing Technology in Precast Concrete Mass Production Industry. *Lect. Notes Civ. Eng.* **2022**, *201*, 207–221. [CrossRef]
5. Pasupathy, K.; Ramakrishnan, S.; Sanjayan, J. 3D concrete printing of eco-friendly geopolymer containing brick waste. *Cem. Concr. Compos.* **2023**, *138*, 104943. [CrossRef]
6. Qian, H.; Hua, S.; Yue, H.; Feng, G.; Qian, L.; Jiang, W.; Zhang, L. Utilization of recycled construction powder in 3D concrete printable materials through particle packing optimization. *J. Build. Eng.* **2022**, *61*, 105236. [CrossRef]

7. Khan, M.; McNally, C. A holistic review on the contribution of civil engineers for driving sustainable concrete construction in the built environment. *Dev. Built Environ.* **2023**, *16*, 100273. [CrossRef]
8. Chen, K.; Liu, Q.; Chen, B.; Zhang, S.; Ferrara, L.; Li, W. Effect of raw materials on the performance of 3D printing geopolymer: A review. *J. Build. Eng.* **2024**, *84*, 108501. [CrossRef]
9. Lu, Y.; Xiao, J.; Li, Y. 3D printing recycled concrete incorporating plant fibres: A comprehensive review. *Constr. Build. Mater.* **2024**, *425*, 135951. [CrossRef]
10. Moghayedi, A.; Mahachi, J.; Lediga, R.; Mosiea Ts Phalafala, E. Revolutionizing affordable housing in Africa: A comprehensive technical and sustainability study of 3D-printing technology. *Sustain. Cities Soc.* **2024**, *105*, 105329. [CrossRef]
11. Yu, H.; Wen, B.; Zahidi, I.; Ming Fai, C.; Madsen, D.Ø. Constructing the future: Policy-driven digital fabrication in China's urban development. *Results Eng.* **2024**, *22*, 102096. [CrossRef]
12. Aslani, F.; Zhang, Y. *14—Sustainable 3D Printed Concrete Structures Using High-Quality Secondary Raw Materials, Sustainable Concrete Materials and Structures*; Woodhead Publishing: Cambridge, UK, 2024; pp. 399–443. [CrossRef]
13. Pons-Valladares, O.; Casanovas-Rubio, M.D.M.; Armengou, J.; de la Fuente, A. Approach for sustainability assessment for footbridge construction technologies: Application to the first world D-shape 3D-Printed fiber-reinforced mortar footbridge in Madrid. *J. Clean. Prod.* **2023**, *394*, 136369. [CrossRef]
14. Panda, B.; Chandra Paul, S.; Jen Tan, M. Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material. *Mater. Lett.* **2017**, *209*, 146–149. [CrossRef]
15. 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]
16. 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]
17. Panda, B.; Unluer, C.; Tan, M.J. Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing. *Cem. Concr. Compos.* **2018**, *94*, 307–314. [CrossRef]
18. 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.* **2021**, *281*, 123558. [CrossRef]
19. Li, V.C.; Bos, F.P.; Yu, K.; McGee, W.; Ng, T.Y.; Figueiredo, S.C.; Nefs, K.; Mechtcherine, V.; Nerella, V.N.; Pan, J.; et al. On the emergence of 3D printable Engineered, Strain Hardening Cementitious Composites (ECC/SHCC). *Cem. Concr. Res.* **2020**, *132*, 106038. [CrossRef]
20. Biernacki, J.J.; Bullard, J.W.; Sant, G.; Brown, K.; Glasser, F.; Jones, S.; Ley, T.; Livingston, R.; Nicoleau, L.; Olek, J.; et al. Cements in the 21st century: Challenges, perspectives, and opportunities. *J. Am. Ceram. Soc.* **2017**, *100*, 2746–2773. [CrossRef]
21. Chen, Y.; Chaves Figueiredo, S.; Li, Z.; Chang, Z.; Jansen, K.; Çopuroğlu, O.; Schlangen, E. Improving printability of limestone-calcined clay-based cementitious materials by using viscosity-modifying admixture. *Cem. Concr. Res.* **2020**, *132*, 106040. [CrossRef]
22. 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]
23. Weng, Y.; Li, M.; Ruan, S.; Wong, T.N.; Tan, M.J.; Ow Yeong, K.L.; 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]
24. Bhattacherjee, S.; Basavaraj, A.S.; Rahul, A.V.; Santhanam, M.; Gettu, R.; Panda, B.; Schlangen, E.; Chen, Y.; Copuroglu, O.; Ma, G.; et al. Sustainable materials for 3D concrete printing, Cement and Concrete. *Composites* **2021**, *122*, 104156. [CrossRef]
25. 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]
26. Wasti, S.; Adhikari, S. Use of Biomaterials for 3D Printing by Fused Deposition Modeling Technique: A Review. *Front. Chem.* **2020**, *8*, 00315. [CrossRef] [PubMed]
27. Muthukrishnan, S.; Ramakrishnan, S.; Sanjayan, J. Effect of microwave heating on interlayer bonding and buildability of geopolymer 3D concrete printing. *Constr. Build. Mater.* **2020**, *265*, 120786. [CrossRef]
28. Khan, S.A.; Koç, M.; Al-Ghamdi, S.G. Sustainability assessment, potentials and challenges of 3D printed concrete structures: A systematic review for built environmental applications. *J. Clean. Prod.* **2021**, *303*, 127027. [CrossRef]
29. Dey, D.; Srinivas, D.; Panda, B.; Suraneni, P.; Sitharam, T.G. Use of industrial waste materials for 3D printing of sustainable concrete: A review. *J. Clean. Prod.* **2022**, *340*, 130749. [CrossRef]
30. Bong, S.H.; Nematollahi, B.; Nazari, A.; Xia, M.; Sanjayan, J. Method of optimisation for ambient temperature cured sustainable geopolymers for 3D printing construction applications. *Materials* **2019**, *12*, 902. [CrossRef]
31. Bong, S.H.; Xia, M.; Nematollahi, B.; Shi, C. Ambient temperature cured 'just-add-water' geopolymer for 3D concrete printing applications. *Cem. Concr. Compos.* **2021**, *121*, 104060. [CrossRef]
32. Chen, Y.; Li, Z.; Figueiredo, S.C.; Çopuroğlu, O.; Veer, F.; Schlangen, E. Limestone and Calcined Clay-Based Sustainable Cementitious Materials for 3D Concrete Printing: A Fundamental Study of Extrudability and Early-Age Strength Development. *Appl. Sci.* **2019**, *9*, 1809. [CrossRef]
33. Imtiaz, L.; Ur Rehman, S.K.; Memon, S.A.; Khan, M.K.; Javed, M.F. A review of recent developments and advances in eco-friendly geopolymer concrete. *Appl. Sci.* **2020**, *10*, 7838. [CrossRef]

34. 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]
35. Panda, B.; Tay, Y.W.D.; Paul, S.C.; Tan, M.J. Current challenges and future potential of 3D concrete printing. *Mater. Und Werkst.* **2018**, *49*, 666–673. [CrossRef]
36. Hack, N.; Dörfler, K.; Walzer, A.N.; Wangler, T.; Mata-Falcón, J.; Kumar, N.; Buchli, J.; Kaufmann, W.; Flatt, R.J.; Gramazio, F.; et al. Structural stay-in-place formwork for robotic in situ fabrication of non-standard concrete structures: A real scale architectural demonstrator. *Autom. Constr.* **2020**, *115*, 103197. [CrossRef]
37. Singh, A.; Wang, Y.; Zhou, Y.; Sun, J.; Xu, X.; Li, Y.; Liu, Z.; Chen, J.; Wang, X. Utilization of antimony tailings in fiber-reinforced 3D printed concrete: A sustainable approach for construction materials. *Constr. Build. Mater.* **2023**, *408*, 133689. [CrossRef]
38. 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]
39. Zhong, H.; Zhang, M. 3D printing geopolymers: A review. *Cem. Concr. Compos.* **2022**, *128*, 104455. [CrossRef]
40. Şahin, H.G.; Mardani-Aghabaglou, A. Assessment of materials, design parameters and some properties of 3D printing concrete mixtures; a state-of-the-art review. *Constr. Build. Mater.* **2022**, *316*, 125865. [CrossRef]
41. Nilimaa, J. Smart materials and technologies for sustainable concrete construction. *Dev. Built Environ.* **2023**, *15*, 100177. [CrossRef]
42. Zhong, H.; Zhang, M. Engineered geopolymer composites: A state-of-the-art review. *Cem. Concr. Compos.* **2023**, *135*, 104850. [CrossRef]
43. Tinoco, M.P.; de Mendonça, É.M.; Fernandez, L.I.C.; Caldas, L.R.; Reales, O.A.M.; Toledo Filho, R.D. Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: A systematic literature review. *J. Build. Eng.* **2022**, *52*, 104456. [CrossRef]
44. Qaidi, S.; Yahia, A.; Tayeh, B.A.; Unis, H.; Faraj, R.; Mohammed, A. 3D printed geopolymer composites: A review. *Mater. Today Sustain.* **2022**, *20*, 100240. [CrossRef]
45. 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]
46. Das, A.K.; Agar, D.A.; Rudolfsson, M.; Larsson, S.H. A review on wood powders in 3D printing: Processes, properties and potential applications. *J. Mater. Res. Technol.* **2021**, *15*, 241–255. [CrossRef]
47. Lazorenko, G.; Kasprzhitskii, A. Geopolymer additive manufacturing: A review. *Addit. Manuf.* **2022**, *55*, 102782. [CrossRef]
48. Khalil, A.; Wang, X.; Celik, K. 3D printable magnesium oxide concrete: Towards sustainable modern architecture. *Addit. Manuf.* **2020**, *33*, 101145. [CrossRef]
49. Dörfler, K.; Dielemans, G.; Lachmayer, L.; Recker, T.; Raatz, A.; Lowke, D.; Gerke, M. Additive Manufacturing using mobile robots: Opportunities and challenges for building construction. *Cem. Concr. Res.* **2022**, *158*, 106772. [CrossRef]
50. Adaloudis, M.; Bonnin Roca, J. Sustainability tradeoffs in the adoption of 3D Concrete Printing in the construction industry. *J. Clean. Prod.* **2021**, *307*, 127201. [CrossRef]
51. 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]
52. Flatt, R.J.; Wangler, T. On sustainability and digital fabrication with concrete. *Cem. Concr. Res.* **2022**, *158*, 106837. [CrossRef]
53. Liu, J.; Nguyen-Van, V.; Panda, B.; Fox, K.; Du Plessis, A.; Tran, P. Additive Manufacturing of Sustainable Construction Materials and Form-finding Structures: A Review on Recent Progresses. *3d. Print. Addit. Manuf.* **2022**, *9*, 12–34. [CrossRef]
54. Amran, M.; Abdelgader, H.S.; Onaizi, A.M.; Fediuk, R.; Ozbakkaloglu, T.; Rashid, R.S.M.; Murali, G. 3D-printable alkali-activated concretes for building applications: A critical review. *Constr. Build. Mater.* **2022**, *319*, 126126. [CrossRef]
55. Ahmed, G.H. A review of "3D concrete printing": Materials and process characterization, economic considerations and environmental sustainability. *J. Build. Eng.* **2023**, *66*, 105863. [CrossRef]
56. Meibodi, M.A.; Jipa, A.; Giesecke, R.; Shammas, D.; Bernhard, M.; Leschok, M.; Graser, K.; Dillenburger, B. Smart slab: Computational design and digital fabrication of a lightweight concrete slab. In *Recalibration on Imprecision and Infidelity—Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture, Acadia, LA, USA, 18–20 October 2018*; ACADIA: Charleston, SC, USA, 2018; pp. 434–443.
57. Markin, V.; Krause, M.; Otto, J.; Schröfl, C.; Mechtcherine, V. 3D-printing with foam concrete: From material design and testing to application and sustainability. *J. Build. Eng.* **2021**, *43*, 102870. [CrossRef]
58. Abdalla, H.; Fattah, K.P.; Abdallah, M.; Tamimi, A.K. Environmental footprint and economics of a full-scale 3d-printed house. *Sustainability* **2021**, *13*, 11978. [CrossRef]
59. 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]
60. Tahmasebinia, F.; Sepasgozar, M.E.S.; Shirowzhan, S.; Niemela, M.; Tripp, A.; Nagabhyrava, S.; Mansuri, K.Z.; Alonso-Marroquin, F. Criteria development for sustainable construction manufacturing in Construction Industry 4.0: Theoretical and laboratory investigations. *Constr. Innov.* **2020**, *20*, 379–400. [CrossRef]
61. 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]
62. Albidah, A.S. Effect of partial replacement of geopolymer binder materials on the fresh and mechanical properties: A review. *Ceram. Int.* **2021**, *47*, 14923–14943. [CrossRef]

63. Wolfs, R.; Bos, D.; Salet, T. Lessons learned of project Milestone: The first 3D printed concrete house in the Netherlands. *Mater. Today Proc.* **2023**. [CrossRef]
64. Beltrami, M.; Orzes, G.; Sarkis, J.; Sartor, M. Industry 4.0 and sustainability: Towards conceptualization and theory. *J. Clean. Prod.* **2021**, *312*, 127733. [CrossRef]
65. Hossain, M.A.; Zhumabekova, A.; Paul, S.C.; Kim, J.R. A review of 3D printing in construction and its impact on the labor market. *Sustainability* **2020**, *12*, 8492. [CrossRef]
66. Senthilnathan, S.; Raphael, B. Using Computer Vision for Monitoring the Quality of 3D-Printed Concrete Structures. *Sustainability* **2022**, *14*, 15682. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.