

Review

3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review

Maša Žujović , Radojko Obradović, Ivana Rakonjac  and Jelena Milošević * 

Faculty of Architecture, University of Belgrade, 11000 Belgrade, Serbia

* Correspondence: jelena@arh.bg.ac.rs

Abstract: The proliferation of digital technologies considerably changed the field of architecture. Digital fabrication pushes architecture into an unexpected new domain of previously unachievable complexity, detail, and materiality. Understanding these technologies' impact can help direct future research, innovate design and construction processes, and improve the education of future professionals. However, comprehensive reviews offering a holistic perspective on the effects of 3D printing technologies on architecture are limited. Therefore, this study aims to provide a systematic review of state-of-the-art research on 3D printing technologies in architectural design and construction. The review was performed using three major databases, and selected peer-reviewed journal articles published in the last ten-year period were included in quantitative and qualitative analyses. Using bibliometric analysis, the research progress is summarized through the identified trend of the annual number of articles, prominent authors and co-authorship network, and key topics in the literature organized in three clusters. Further, content analysis of selected articles enabled coding cluster themes. Moreover, the analysis differentiated two categories of 3D printing technologies based on the scale of the system, elaborating their peculiarities in terms of materials, methods, and applications. Finally, challenges and promising directions for future work and research challenges are discussed.

Keywords: architecture; design; digital fabrication; construction industry; additive construction; additive manufacturing; rapid prototyping; 3D printing; models; prototypes



Citation: Žujović, M.; Obradović, R.; Rakonjac, I.; Milošević, J. 3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review. *Buildings* **2022**, *12*, 1319. <https://doi.org/10.3390/buildings12091319>

Academic Editor: Derek Clements-Croome

Received: 31 July 2022

Accepted: 23 August 2022

Published: 28 August 2022

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1. Introduction

The construction industry had to introduce innovative procedures and technologies, such as digital fabrication, to respond to architectural design requests for flexibility, complexity, high performance, detail, personalization of material, and technology [1–5]. Automation in architecture [6–8] is offered as an alternative to inefficient and wasteful production models. This model of digital architecture is expected to make a difference and positive change in the built environment. Consequently, architectural discipline is expected to work towards fully automated production forms and processes that promote equality, sustainability, democracy, diversity, and inclusiveness.

Understanding the effects of advanced technologies on architectural discipline can guide future research, innovate design and construction methods, and enhance education. Accordingly, the purpose of this work is to discuss state-of-the-art digital fabrication technologies in architecture, focusing on 3D printing (3DP). Out of all digital fabrication technologies, 3DP is chosen because of its operational potential in the architecture engineering and construction (AEC) industry. Applying this technology could enable the fabrication of complex structures more sustainably with less material and without the need for traditional formwork. Another advantage is that 3DP can be used in all stages of the design process, from form-finding prototypes to the fabrication of full-scale structures.

Additive manufacturing (AM) is the procedure of successive printing layers of materials formed on top of one another [9]. The terms “additive manufacturing” and “3D printing” are often used synonymously to denote the construction of an object through the

successive building of material. 3DP technology has been developing since the mid-1980s when Charles Hull developed the first commercial 3D printer [10]. Pegna developed the first large-scale concrete printer in the late 1990s, which enabled the use of 3DP in the construction industry [11]. Although this technology started developing over 25 years ago, its rapid development started much later.

The study by Chung et al. [12] showed that the number of papers on using 3DP technology in the construction industry has increased in the last ten years. Previous indicates a growing interest in applying and developing this technology in the construction sector and, consequently, in architecture. With the growing number of papers, many authors have reviewed this technology and its impact and use in construction [13–24]. These studies, even though extensive, tend to focus on specific aspects of technology and its application. However, while there are studies covering different aspects of 3DP technology, current research lacks the systematization needed to provide a general insight into all the applications of this technology in architecture.

For example, studies [12,25,26] focus on 3DP technology from a more technical standpoint, discussing printing equipment specifications and limitations. Another common research topic is the development of printing materials. Materials used for 3DP construction are often presented from a material science perspective, making those researches too technically oriented for this paper, as seen in [27,28]. On the other hand, several authors are focusing their research on specific aspects of the usage of the 3DP technology, such as its impact on the labor market [29] or environmental impact [30]. There are also papers that focus on the possible applications of 3DP in architecture, but they mainly review specific research projects such as printed large-scale architectural elements [31].

This research aims to conduct a comprehensive systematic literature review (SLR) on the impact of state-of-the-art 3DP technology on architectural design and construction. Starting from the research question “What is the scope of application of 3DP technology in architecture?”, three major databases were searched, and relevant publications were selected and analyzed. The analysis generated findings on the trend of the annual number of articles, keyword co-occurrence, and clustering. The further analysis enabled the identification of the main research themes as well as categorization based on the scale of 3DP systems. Finally, this discussion could be relevant to other researchers because it summarizes up-to-date accomplishments and trends of development to better identify experiences and scientific results as well as to recognize possibilities for future research, innovation, and opportunities for applications of this technology in the AEC industry.

2. Materials and Methods

An SRL method was used to conduct research—identify, select, critically evaluate research literature, and create new perspectives. The method was applied because it provides theoretical knowledge and insights into current tendencies related to the research topic [32]. An SRL was conducted following Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines [33,34]. Following these guidelines, a systematic protocol was used to generate and evaluate the collection of articles that included three phases: (1) data search, (2) data selection, and (3) data analysis.

The keyword method [35] was applied in the first step for searching databases and collecting articles. The search results were then refined to exclude all papers irrelevant to the study. Firstly, all keywords from disciplines other than architecture or construction were eliminated. Next, papers were evaluated based on the titles and the abstracts to select the most relevant articles. Finally, papers were scanned in full text to exclude any irrelevant texts that may have remained. Additionally, the snowballing method [36] was used to search for additional literature by going through reference lists of the selected papers. The refinement process was repeated on that additional body of research until all selected articles were deemed relevant for the review. The formed literature sample was then subjected to quantitative and qualitative analyses.

2.1. Data Search

SLRs enabled covering all published literature (within selected databases) that mostly responds to a particular research question using carefully chosen keyword strings. Furthermore, the method empowered researchers to narrow search results by using pre-established exclusion criteria to obtain a relevant final sample of papers that can effectively address their researched problem [35].

Table 1 summarizes the main parameters and corresponding values used in the database search (according to the PRISMA checklist).

Table 1. Search criteria.

Parameters	Values
Information source	<i>Scopus, Web of Science, Google Scholar</i>
Search Strategy	(a) Keyword method [using keyword strings: “3D printing” AND “architecture” OR “design” OR “construction” OR “rapid prototyping” OR “education”] and (b) Snowballing method
Eligibility criteria	(a) Document type: journal papers; (b) Search language: title, abstract, key words, and full text only in English; (c) Data range: 2013–present; (d) Last update: 25 June 2022

Data collection was done by searching three main databases: *Scopus, Web of Science, and Google Scholar*. Selected databases cover a wide range of scientific publications, including some of the most relevant journals. The scope of the literature was restricted to peer-reviewed journal papers, eliminating other types of publications such as books or conference proceedings due to the immense volume of scientific works published each year. Different databases were used to provide a variety of indexed journals for searching.

Search limitations, set in advance, were the same for all databases. In addition, the observed publication period includes the last ten years, from 2013–present, excluding early-access articles and articles still in the publishing phase. This time frame was established because 3DP technology is relatively new in common use and is fast-developing, so this timeframe was deemed most relevant for a state-of-the-art review. Lastly, this study included only articles written in the English language.

The keyword strings used were intentionally vague to cover all possible application areas. For example, the initial string for searching the *Google Scholar* database was [architecture OR CONSTRUCTION “3D print *”], resulting in over 15,600 initial results, which were later narrowed down to 351 by eliminating keywords from science fields. The final *Google Scholar* keyword string was [architecture OR CONSTRUCTION “3D print *-biology -medicine -computer -molecular -biological -medical -bionic -cell -tissue -bio -rheological -micro -energy -BIM -chemical -chemistry -fashion -electrical]. A similar methodology was then applied for searching two other databases considering the specifics of each search engine.

The snowballing method was used in addition to the keyword search to collect more data and find papers that might have been missed. The term “snowballing” describes the process of finding more publications by analyzing a paper’s reference list or its citations. According to guidelines for snowballing in systematic literature studies [36], using references and citations of the analyzed papers for finding new literature is called backward and forward snowballing. In this study, backward snowballing was mainly used.

Figure 1 outlines the SRL procedure and recaps the number of publications at the end of each process stage.

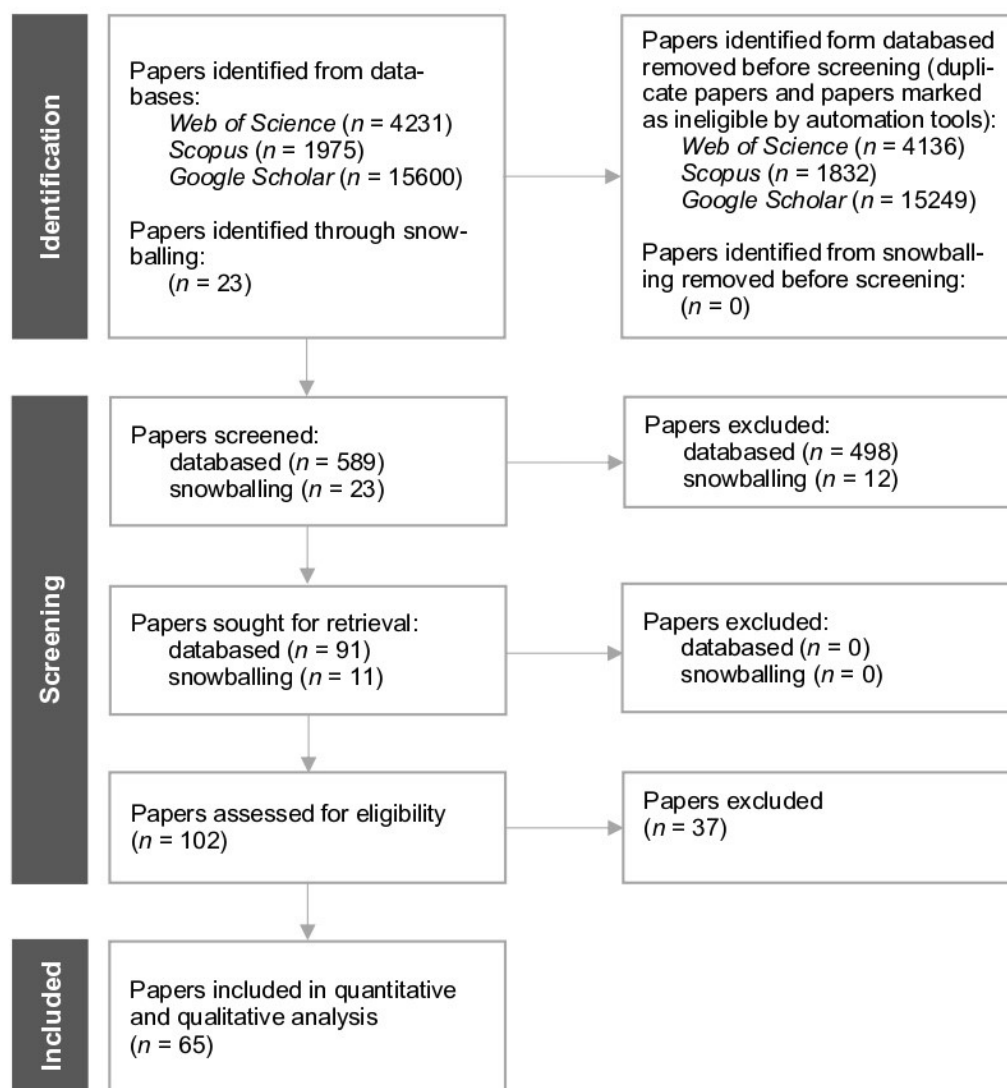


Figure 1. PRISMA flow diagram of literature review.

2.2. Data Selection

After conducting initial searches, the collected data were then further assessed. As was mentioned in the previous section, basic searches were performed using the keyword method. Both abstract and publication keywords were searched for “architecture” and “3D printing”, as those two terms are the most relevant for this review. Additionally, the words “design”, “construction”, “rapid prototyping”, and “education” were included under the assumption that this search criterion was most likely to cover the main fields where it is expected to find articles relevant to architecture.

After the initial search, one repeating trend was observed in all three databases. The term architecture is too broad and can be found in different industries such as computer science and biomedical sciences, where 3DP technology is also extensively researched and used in practice. This problem was resolved by filtering out all keywords and research topics associated with computer sciences, electronics, the biomedical field, and chemistry. After repeating this process in all three searches, articles that were left were, for the most part, related to 3D printing in the AEC industry.

After filtering inadequate papers, duplicates, and those texts that the authors did not have access to, this process generated 91 papers. These were then reviewed in full text to eliminate papers irrelevant for further analysis. While reviewing those papers, snowballing

added another 23 articles to be assessed in full text, out of which 11 were used in the final literature sample.

Since AEC is a wider field than just architecture, there were still some papers that focused on material science or technical engineering details of 3DP technology. This body of research was then narrowed to the articles relevant to the field of architecture by going through full texts. After going through full texts, some articles were eliminated because they were in the field of mechanical engineering, civil engineering, or material science with no overlap with the use of 3DP technology in architecture but rather focusing on chemical or structural properties of the material and formwork. This final refinement resulted in 65 articles for which analysis is discussed in the next section.

A team of different researchers was assembled to guarantee the validity of the article selection procedure and avoid bias. Two researchers had the task to conduct activities of the three phases—identification of data from databases and through the snowballing method, screening papers, and assessing papers for eligibility. The other two researchers were responsible for overseeing and reviewing the process to ensure forming a relevant literature sample and the quality of the research.

2.3. Data Analysis

Selected papers were analyzed using quantitative bibliometric analysis, a type of statistical and applied mathematical analysis of the bibliographic units [37], frequently used in recent years for analysis, evaluation, and prediction of the status of different research fields [38]. A key bibliometrics technique, network analysis, was used in this study. Network analysis facilitates the visualization of the intricate connection between articles and citations in different journals. As a result, the information gathering process can be made more straightforward, and the knowledge structure can be made more evident by describing nodes and the connected network framework to clarify the relationship between articles [38].

For the implementation of network analysis in this research, text-mining software VOSviewer (Visualization of Similarities viewer) was used. This software visually analyzes similar research and uses the co-occurrence matrix for the layout to create a knowledge map—a network made of nodes and links that connect them [39]. Using VOSviewer, keyword co-occurrence rate analysis was conducted. Consequently, a sample of the literature generated in the bibliometric search was imported into VOSviewer for the analysis, which produced visual networks of keywords showing their influence and level of impact in the field.

In the following step of the research, qualitative content analysis was conducted based on the results of the bibliometric analysis—the network of keywords with the clusters based on their co-occurrence rate. Previous study was done to further evaluate the state-of-the-art of 3DP technology applications in architecture. The purpose of the qualitative study was to analyze and systematize the available research in more detail since the obtained results still lack classification.

Qualitative analysis was conducted on the sample of selected articles, with the aim to give a theme to each cluster. The procedure used had the following steps: (1) select a cluster; (2) search each word from that cluster in the full text of all articles included in the sample; (3) read the context of a word where it appears in the corresponding articles; (4) select common articles having most of the words from that the particular cluster; (5) carefully read the selected articles to find the central idea or theme; and (6) assign a theme to that cluster. The same procedure was repeated for all the clusters in the network.

3. Results

This section presents the results of bibliometric analysis and qualitative analysis organized in subsequent subheadings.

3.1. Bibliometric Analysis

3.1.1. Articles Publishing Trends

The number of papers published in a field shows the direction of development and scope of knowledge. Within the scope of retrieval, Figure 2 illustrates the trend of an annual number of articles on 3DP in architecture published over the past 10 years, from 2013 to the present. Out of 65 selected papers, 52 (80%) were published in the last 5 years. Moreover, 35 of the 65 papers, making 53.8% of the total number of papers, were published in the last 3 years. Previous study shows a trend of rapid growth in the number of publications in recent years, as was noted in the research by [40]. A similar trend of growth in the number of publications over the last decade regarding the impact of 3DP technology in the construction industry was also shown in the study [16]. However, no articles that review the published papers on the impact of 3DP on the field of architecture were found. Additionally, a similar trend in the number of published papers can also be observed in the publication year data collected from the *Scopus* database after the initial (non-filtered) search that produced 143 articles, which are given in Appendix A (Figure A1).

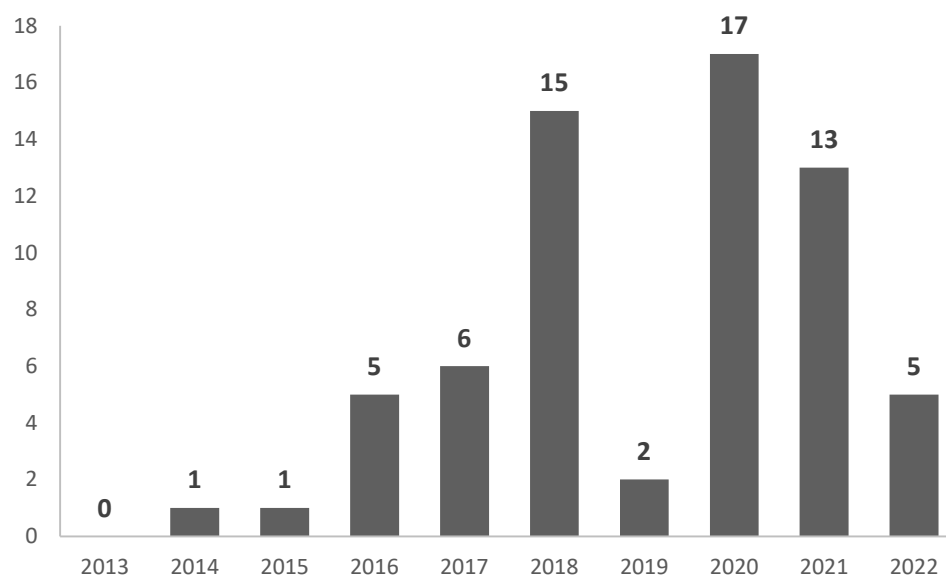


Figure 2. Publication rate of filtered articles on 3DP in architecture.

As it can be observed, the number of available papers increased significantly between 2017 and 2018. Until then, the more often research focus was on 3DP application in design and education, as 3DP was still an emerging trend in the construction industry. However, in 2017, several review articles were published focusing on large-scale applications in the construction industry [20,25], which points to the significant shift in the research trends. Furthermore, around this time, several new 3DP methods such as particle-bed 3DP [41] or 3D printing of ultra-high-performance concrete [42] were presented, opening new possibilities for future research.

3.1.2. Source Journals

The journal where a retrieved article was published is referred to as the source journal. A literature sample of 65 articles was published in 37 different journals. The articles were mainly published in journals related to buildings and constructions, civil and structural engineering, architecture, computer graphics and computer-aided design, modeling and simulation, and material sciences. The top 20 source journals from which works on 3DP in architecture were collected are listed in Table 2 according to Journal Citation Reports (JCR) Impact Factor (IF).

Table 2. Source journals for articles on 3DP in architecture in the analyzed literature sample.

Journals	No. of Papers	SJR (2021)	IF (2021)
<i>Science Robotics</i>	1	Q1	27.541
<i>Cement and Concrete Research</i>	8	Q1	11.958
<i>Virtual and Physical Prototyping</i>	3	Q1	10.962
<i>Automation in Construction</i>	16	Q1	10.517
<i>Composites Part A: Applied Science and Manufacturing</i>	1	Q1	9.463
<i>Construction and Building Materials</i>	1	Q1	7.693
<i>Engineering Structures</i>	1	Q1	5.582
<i>3D Printing and Additive Manufacturing</i>	2	Q1	5.355
<i>Journal of Sustainable Cement-Based Materials</i>	1	Q1	5.328
<i>Journal of Constructional Steel Research</i>		Q1	4.349
<i>Rapid Prototyping Journal</i>	1	Q1	4.043
<i>Archives of Civil and Mechanical Engineering</i>	1	Q1	4.042
<i>Sustainability</i>	1	Q2	3.889
<i>Materials</i>	1	Q2	3.748
<i>Biomimetics</i>	1	Q2	3.743
<i>International Journal of Advanced Manufacturing Technology</i>	1	Q1	3.563
<i>Buildings</i>	2	Q1	3.324
<i>Computer Applications in Engineering Education</i>	1	Q1	2.109
<i>Transportation Research Record</i>	1	Q2	2.019
<i>Infrastructures</i>	2	Q2	/

Two publications have significantly more 3DP-related articles than the others: *Automation in Construction* (16 papers) and *Cement and Concrete Research* (8 papers). These two publications together account for 36.9% of the total papers. Since 3DP is a technology based on AM processes, which are closely related to digitalization and automation, articles from the journal *Automation in Construction* account for the largest portion of the published literature. The analysis also indicates that the material used in 3DP is commonly concrete since the second most represented journal is *Cement and Concrete Research*. According to the journal occurrence, the study on 3DP mostly focuses on expanding knowledge of materials and processes. Four journals had an occurrence rate of two or more articles—*Virtual and Physical Prototyping*, *3D Printing and Additive Manufacturing*, *Buildings*, and *Infrastructures*.

Automation in Construction is highly active in the construction 3DP, covering all aspects of the use of information technologies in the design, engineering, construction, maintenance, and management of constructed facilities. *Cement and Concrete Research*, on the other hand, primarily introduces research accomplishments in material science with a focus on cement materials. Nevertheless, both journals significantly impact the building and construction field, having a Q1 score based on the SCImago Journal Ranking (SJR) system and high impact factors (IF). *Virtual and Physical Prototyping* has a Q1 score in computer graphics and computer-aided design, industrial and engineering manufacturing, and modeling and simulation, and *Buildings* has a Q1 score for architecture based on SJR.

The study by Ning et al. [16] produced similar results in terms of publication distribution, with *Automation in Construction* and *Cement and Concrete Research* being the second and third most occurring publications in their *Web of Science* search for the period between 2013 and 2020. Their study focused on the review of the 3DP in the construction industry, which is a narrower field than architecture. For that reason, the most prevalent journal in their search was *Construction and Building Materials*. However, only one paper from this journal is included in the literature sample since the journal has a more technical focus on 3DP technology and materials, which is less relevant for the scope of this study.

3.1.3. Keywords Analysis and Clustering

Keyword co-occurrence analysis can identify keyword aggregation, clarify the development direction, and summarize emerging research in an academic field. Two counting methods were available for keyword analysis: binary and full counting. The binary method

does not account for repetition within an article; it only counts the presence or absence of a term. On the other hand, full counting entails recording each word's occurrence. Because it offers a more thorough understanding of the actual representation of research issues, the full counting method was chosen for this study.

Keywords were selected by scanning repeating words in titles and abstracts of all papers. Word repeating is limited to five times or more to observe emerging research interests. In total, 103 words fit this criterium. For each word, a relevance score was calculated, and then, based on that score, 60% of the words with the highest relevance were used for further analysis to highlight the most influential terms; 62 words were evaluated using this criterion. Table 3 shows selected 25 keywords with strong connection strength.

Table 3. The occurrence and relevance of keywords in the analyzed literature sample.

Keyword	Occurrences	Relevance Score
structure	44	0.6264
industry	39	1.3401
concrete	36	0.9324
student	36	1.3935
model	29	0.6883
construction industry	28	0.9395
3D printing technology	24	0.922
formwork	24	1.2044
education	22	1.2286
environment	21	0.4794
approach	20	0.2337
geometry	18	0.6266
architecture	16	0.4672
fabrication	14	0.8044
production	13	0.8934
framework	12	1.2117
automation	11	0.8441
bridge	11	1.207
case study	11	0.5958
concrete structure	11	1.4197
art	10	0.8032
housing industry	10	2.3917
creativity	9	1.5211
digital fabrication	9	0.7792
3D concrete printing	8	1.2498

In Figure 3, the same sample of words is visualized as a network. Accordingly, keyword mapping shows three distinct clusters (green, red, and blue), each representing one area where 3DP technology is used. Due to the number of terms and connections, the red cluster is the biggest and most complex. The backbone of this cluster are the terms "structure", "concrete", "fabrication", and "architecture", indicating that a significant number of analyzed papers focus application of the 3DP technology in design projects. However, when analyzing the nodes with the highest combined occurrence rate and link strength, the most prevalent terms are "structure", "student", "construction industry", "industry", and "concrete." Those depict the main areas of interest and research.

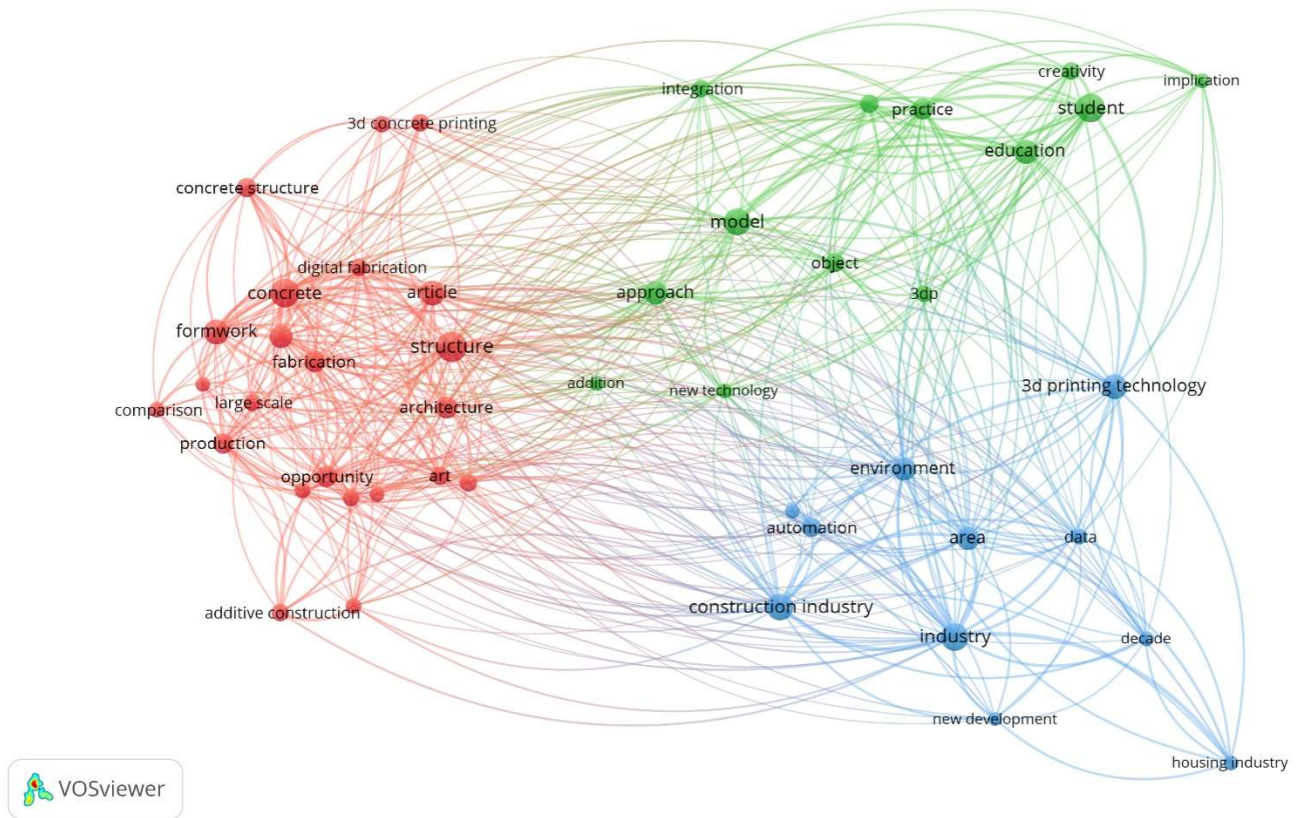


Figure 3. Network visualization of occurrence of keywords and clusters in the analyzed literature sample.

As this paper aims to obtain a comprehensive overview of the connection between 3DP technology and the field of architecture, the terms “3D printing technology” and “architecture” were investigated more closely concerning their connections to various clusters in the network of keywords. The results of this analysis are presented in Figure 4.

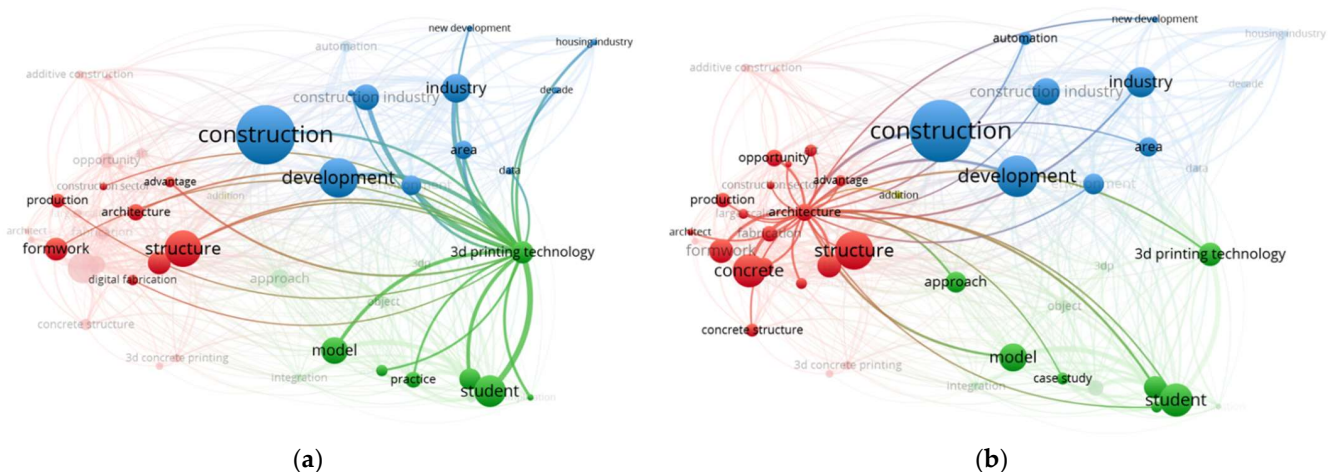


Figure 4. Connections with different terms and clusters in the network of analyzed literature sample for terms: (a) “3D printing technology” and (b) “architecture”.

Both terms had a strong connection with all clusters. “Architecture” is less dominant since not all articles whose research problems are in the domain of architecture use this term specifically in abstracts or titles. Adversely, they opt for other terms in the architecture field that are more specific to their research, such as “construction”. However, it can be

seen that “architecture” has links with most terms that have high relevance in terms of occurrence and link strength.

3.2. Content Analysis

3.2.1. Cluster Themes

All selected articles underwent qualitative analysis, and each emerging cluster from the keyword co-occurrence analysis (Figure 3) was then grouped under a particular theme following the procedure described in Section 2.3., i.e., Data Analysis, of this paper. The clusters and their associated themes and selected keywords are summarized in Table 4.

Table 4. Clusters and themes in the analyzed literature sample.

No.	Cluster	Theme	No. of Keywords	Representative Keywords	Tag
1	Green	Application of 3DP technology in education	17	student model education creativity	Education
2	Red	Application of 3DP technology in design	30	structure concrete fabrication architecture production	Design
3	Blue	Application of 3DP technology in construction industry	15	3DP technology construction industry automation new development	Construction

Theme 1: 3DP Technology in Education

The theme of the first green cluster is the implementation of 3DP in education. The papers relating to this topic focus mostly on the effects of the application of 3DP technology in the architectural design curriculum. The studies have shown that the integration of 3DP technology in the design process can incentivize creative thinking, leading to more complex design solutions compared to traditional teaching methods [43–45]. Many students used 3DP technology for prototyping, which led to increasingly complex designs. In comparison to conventional approaches, 3DP allowed them to create physical models that were far more conceptually and geometrically complex [46,47]. Another benefit of this approach is that the use of AM positively affected students’ spatial cognition, as they were able to view their designs in the physical environment and focus on the overall design concept [48,49]. In most cases, this technology is implemented in the form of standard desktop 3D printers suitable for printing small models that can be used during the design process for prototyping presentation models [50]. On the other hand, Anton et al. [31] demonstrate the use of large-scale 3DP technology for printing concrete columns as a part of the Master’s design studio course at ETH Zurich.

Theme 2: 3DP Technology in Design

The second cluster is the biggest in terms of the number of keywords and papers. Furthermore, this cluster covers a wide range of topics related to different aspects of the design and fabrication process. Based on the occurrence rate and link strength, the most dominant words in this cluster are “structure”, “concrete”, “fabrication”, “architecture”, and “production”, indicating several topics. However, there is a significant overlap between papers covering topics represented in this and the other two clusters. For example, the impact of AM technologies on the design process can be observed in educational settings [44,45] and the construction industry [19,23,26,51–53]. Another central theme is the design and fabrication of large-scale concrete structures. Since 3DP concrete is an emerging

trend, researchers are still exploring this technology by testing its geometric and structural potentials [54,55]. Correspondingly, authors are testing different design and fabrication approaches for 3DP concrete, mainly direct printing of structural material [31,56] as opposed to the 3DP formworks [52,55]. Both approaches have unique advantages and disadvantages in terms of geometric complexity and structural characteristics of printed forms. In general, the main subject of this cluster is the potential of integrating AM technologies into the design process.

Theme 3: 3DP Technology in Construction Industry

Most authors in this cluster focus their research on 3DP technology development and applications in the construction industry. The previous is also evident from the keyword analysis results that identified many words connected to the construction industry and automation. Two main research areas covered in articles related to this cluster are the application of 3DP for construction-scale AM projects and large-scale prototypes. The construction scale projects can be either full-scale buildings or prefabricated building elements. 3DP is currently used in many construction projects, from housing units [14,23] to bridges [54,57,58], and applied for both in situ and prefabricated elements. While complete 3DP construction projects often rely on in situ fabrication methods, research favors the pre-fabrication of 3DP architectural elements, as it allows the fabrication of custom designs [55]. Large-scale prototypes are usually test models of building elements that explore new fabrication methods or materials and are still not ready for full-scale application [31,59]. Another common research topic is 3DP technology or fabrication methods used in the construction industry, with several authors presenting new methods [41,42,51,52,60] or reviewing and systematizing existing ones [23,25,61].

3.2.2. Categories Based on Scale

Although all reviewed papers on the application of 3DP technology in architecture can be classified into at least one of the clusters, their focus can also be put into one of two categories based on the criteria of scale: large-scale systems or small-scale systems. Leach [62] explored the implications of scaling in 3DP and its impact on using such technology in architecture. The matter of scale is important because when scaling up, which is required for the application of 3DP in the construction industry, material properties become increasingly more important. Consequently, as scale progresses, materials and technology become more of a limitation than a form of complexity. On the other hand, models used for design research or representation do not need to have the structural properties of a full-scale structure. For this reason, different technologies and materials are used to adapt to the needed scale. The features of the different scale 3DP systems (materials, methods, and applications) are summarized in Table 5.

Category 1: Small-Scale Systems

Small-scale 3DP or rapid prototyping (RP) refers to the technology that is commonly available and uses materials that lack the structural properties required for use in full-scale buildings. This category of 3DP primarily includes more accessible technology, such as desktop 3D printers and other in-home equipment. The technology is selected based on the purpose and complexity of a model.

Systems that are currently in use are based on stereolithography (SLA), fused deposition modeling (FDM), and selective laser sintering (SLS) printing methods [21]. SLA is the oldest of three processes, and it uses a UV laser beam to cure liquid resin into hardened plastic. FDM is the most common of the three. In this method, melted material is extruded in layers on the printer's heated bed, creating an object. Lastly, SLS uses a strong laser beam to cure powdered material. The advantage of SLA and SLS over the FDM is that there is no need for a support structure as printing material serves as support. Aside from three main categories, there are different technologies available today, such as direct metal laser sintering (DMLS) and selective laser melting (SLM) [22].

Table 5. Materials, methods, and applications of 3DP systems categories based on scale.

No.	Category	Materials	Methods	Applications
1	Small-scale	(a) Plastic: <ul style="list-style-type: none"> • Acrylonitrile butadiene styrene (ABS), • Nylon, • Polymers; (b) Metal; (c) Ceramic; (d) Wax; (e) Liquid photosensitive resin.	(a) Stereolithography (SLA); (b) Fused deposition modelling (FDM); (c) Selective Laser Sintering (SLS); (d) Direct Metal Laser Sintering (DMLS); (e) Selective Laser Melting (SLM).	(a) Research: <ul style="list-style-type: none"> • Testing models, • Small-scale prototypes; (b) Education; (c) Design: <ul style="list-style-type: none"> • Exploration models, • Presentation models, • Functional models; (d) Fabrication of building elements.
2	Large-scale	(a) Concrete–cement-based materials; (b) Polymers; (c) Metal; (d) Alternative materials: <ul style="list-style-type: none"> • Foams, • Wax, • Cob, • Clay, • Ceramic. 	(a) Powder based—Binder jetting: <ul style="list-style-type: none"> • D-shape; (b) Extrusion based—Material deposition method (MDM): <ul style="list-style-type: none"> • Contour crafting, • Concrete printing; (c) Hybrid methods: <ul style="list-style-type: none"> • Selective Binder Activation (SBA), • Selective Paste Intrusion (SPI), • Foam spraying, • Tangential Continuity Method (TCM); (d) Formwork printing methods: <ul style="list-style-type: none"> • Robotic formwork FDM, • Sand-printing. 	(a) Research: <ul style="list-style-type: none"> • Testing models, • Large-scale prototypes; (b) Education; (c) Construction industry: <ul style="list-style-type: none"> • Full-scale buildings, • Full-scale building elements.

Materials used in small-scale 3DP are plastic (nylon, polymers, Acrylonitrile butadiene styrene (ABS) or poly lactic acid (PLA)), ceramic, metal, and wax. These materials are mainly used for FDM and SLS. Aside from them, hardened liquid photosensitive resins are employed for SLA to produce plastic material [21].

There are three types of 3DP application for small-scale architectural models: (1) design exploration models [41,44–47,49,50,63–66], (2) design presentation models [43–45,48], and (3) test models [66]. The use of RP can be a part of design research or prototyping of small-scale models of large-scale 3DP constructions. Additionally, several studies have shown the effects of integrating this technology in an educational setting in other design areas such as fashion or product design [45,64]. Design exploration using 3DP models can be found in architectural education within studio design courses at all levels of study. Studies by Ruheili and Hajri [50] and Kim et al. [48], for instance, showed the benefits of the RP's introduction in landscape architecture design courses. On the other hand, a case study by Howaidy and Arafat [43] compared students who made models in traditional ways with those who had access to the RP technology to explore the relationship between the student's design complexity and model-making method.

Another application of RP is for making functional models or small-scale test models for large-scale structures to examine their mechanical or structural properties. For example, Yi et al. [66] described the process of using 3DP technology in prototyping kinetic shading devices. Likewise, the form-finding and testing of vault structures through 3DP were studied by Tomé et al. [65]. Small-scale 3DP technology can sometimes be used for fully functional construction elements, such as optimized steel nodes by Arup [13].

The usual application of 3DP in architecture is also for making presentation models. These kinds of models can be commonly found in education and used as a part of design projects' final presentation [44]. This technology can be available to students as part of the in-class equipment, but universities often have separate shared spaces, such as FabLabs or Maker Spaces [45].

Category 2: Large-Scale Systems

Large-scale 3DP refers to methods of printing elements on a construction scale. Key-word analysis showed that many words with a high occurrence rate are connected to

the construction industry, forming cluster 3. This cluster mostly comprises the use of large-scale 3DCP.

Human-like-scale printed elements that could be applied in the construction industry require adequate structural properties. Therefore, most papers focus either on printing technology or material characteristics. These topics are extensively covered by number of authors [12,13,16,19,23–25,41,51,67–69] in recent years. According to Tay et al. [20], methods used for large-scale printing can be grouped into two main categories: binder jetting and material deposition method (MDM).

Binder jetting is a powder-based process where the liquid binder is deposited in thin layers over a build tray filled with powder to create objects. A well-known binder jetting method is D-shape printing [13,17,70]. This method, developed by architect Enrico Dini, is the oldest large-scale powder-based 3DP method [41] and is similar to SLA. On the other hand, MDM is similar to the FDM method. A nozzle extrudes heated materials in layers on a predefined path. The material then solidifies, creating the object. Two best-known MDM methods are contour crafting [18,43,70], developed by Behrokh Khoshnevis, and concrete printing [13,18].

Some other hybrid methods cannot be classified into any of the categories, such as selective binder activation (SBA), selective paste intrusion (SPI) discussed by Lowke et al. [41] or foam spraying [51], and tangential continuity method (TCM) [70]. Over the years, these methods have been adopted by many companies and research groups. Systematization of these processes can be found in [24]. Additionally, some processes do not rely on printing the actual concrete or building material but rather on printing the formwork. One of these methods is robotic formwork FDM 3D printing, discussed by Burger et al. [52].

Several authors cover the materials used for large-scale 3DP in depth, and their classifications are based on different properties of technological processes. Three common material types applied in these processes are concrete materials, polymers, and metallic materials [13,16,24]. Other materials are also used, including foams [51], wax [70], or cob [53].

Large-scale 3DP is applied in the construction industry in two main areas. One field of research addresses the printing of full-scale structures. Many research groups focus on infrastructure projects, with bridges being the most common. The production process of one of such bridges, the bicycle bridge in Gemert, the Netherlands, is discussed in [58] and [67]. Other research groups and companies focus on developing technology and methods for building full-scale architecture projects such as multistory buildings and houses. An overview of these projects can be found in [13,19,71]. The second field of research focuses development and testing of full-scale building elements such as beams, columns, plates, walls, and even pavilions that serve as large-scale prototypes. These research projects are often developed in academic settings as a form of large-scale RP. Concrete choreography, developed at ETH Zürich [31], is one of these efforts. Other examples from ETH Zürich are branching columns and the future tree pavilion by Burger et al. [52]. Similar initiatives are covered in [41,63,67].

3.2.3. Classification of Articles

Table 6 provides a comprehensive summary of all papers included in this review. It maps each article according to the year of publication, main themes, and scale category of the 3DP system.

Table 6. Literature review summary.

Year	Theme Tag			Scale Category		Author(s) Reference
	Education	Design	Construction	Small-Scale	Large-Scale	
2014	•	•		•		Loy [45]
2015			•		•	Perkins and Skitmore [18]
2016			•		•	Wu et al. [21]
		•	•		•	Labonnote et al. [15]
	•			•		Greenhalgh [47]
		•			•	Gosselin et al. [42]
		•	•		•	Bos et al. [72]
2017		•	•		•	Tay et al. [20]
		•			•	Leach [62]
	•	•		•		Kempton [44]
		•	•		•	Keating et al. [73]
	•			•		Howeidy and Arafat [43]
2018		•	•		•	Duballet et al. [25]
		•			•	X. Zhang et al. [60]
		•	•		•	Wu et al. [22]
		•	•		•	Wolfs et al. [69]
	•			•		Wang et al. [49]
		•	•		•	van Woensel [61]
		•			•	Tomé et al. [65]
		•	•		•	Salet et al. [58]
		•	•		•	Ma et al. [27]
		•	•		•	Lowke et al. [41]
			•		•	Delgado Camacho et al. [24]
		•	•		•	De Schutter et al. [71]
		•	•		•	Buswell et al. [74]
		•	•		•	Buchli et al. [75]
2019		•	•		•	Borg Costanzi et al. [76]
		•			•	Asprone et al. [67]
2020		•			•	J. Zhang et al. [23]
		•			•	Buchanan and Gardner [77]
		•		•		Yi et al. [66]
		•	•		•	Vantyghem et al. [59]
		•	•		•	Siddika et al. [19]
		•			•	Reiter et al. [78]
		•			•	Melenbrink et al. [68]
			•		•	Mehar et al. [79]
		•			•	Martínez-Rocamora et al. [80]
		•			•	Lim et al. [56]
			•		•	Jagoda et al. [81]
			•		•	Hossain et al. [29]
		•	•		•	Han et al. [82]
		•	•		•	Hack et al. [83]
	•	•		•	Gardner et al. [57]	
	•	•		•	El-Sayegh et al. [84]	
	•			•	Carneau et al. [85]	
		•	•	•	Burger et al. [52]	
	•			•	Boumaraf and Inceoglu [46]	

Table 6. Cont.

Year	Theme Tag			Scale Category		Author(s) Reference
	Education	Design	Construction	Small-Scale	Large-Scale	
2021			•		•	Schuldt et al. [40]
	•			•		Ruheili and Hajri [50]
			•		•	Pan et al. [17]
			•		•	Ning et al. [16]
	•			•		Kim et al. [48]
			•		•	Javed et al. [86]
		•	•		•	Gomaa et al. [53]
		•	•		•	García-Alvarado et al. [14]
		•			•	Chung et al. [12]
		•	•		•	Bedarf et al. [51]
		•	•	•	•	Katzer and Skoratko [87]
		•	•	•	•	Abdallah and Estévez [88]
	•	•	•		•	Anton et al. [31]
	2022		•	•		•
		•	•		•	Jipa and Dillenburger [55]
				•		Hu et al. [63]
			•		•	de la Fuente et al. [54]
			•		•	Ali et al. [13]

4. Discussion

This chapter discusses the contribution of this work—summary and mapping of the state-of-the-art research on 3DP technology in architecture in terms of research limitations and challenges within identified major research themes and further directions of work.

4.1. Research Challenges

4.1.1. Challenge 1: Innovating Education

The challenge for architectural education brought by advances in 3DP technologies could be summarized in the following question: How can architectural curriculums be adapted with the use of 3DP technology in order to update learning outcomes and respond to the personnel requirements of professional practice while supporting the learning habits of a new generation of students?

Architectural pedagogy must keep up with the times and prepare students for the professional world and an unpredictable future. When architectural offices and engineering consultancies reinvent themselves to adapt to new social and productive circumstances, future professionals must possess adequate knowledge and skills to act professionally in new working environments. However, beyond teaching students the necessary skills to become competent workers is teaching them skills to design for the future using technology to propose architectural solutions that sustainably address diverse issues.

To answer the challenge, a comprehensive review of the application of 3DP technology in architectural education that summarizes different pedagogical approaches, methods, and practical experiences is necessary. This study identifies that reports on the application of 3DP technology in education usually describe the specific case and individual educational experience (e.g., application in landscape architecture [50]). Although technological advancements could resolve many drawbacks in implementing the technology (especially small-scale printers) and contribute to its wider accessibility [21,43,50], more research is needed to develop new pedagogical approaches and strategies. Furthermore, there should be more studies concerning new curriculums that will overcome reported limitations (e.g., see the study by Kim et al. [48]), their testing in real educational contexts, and evaluation of the effects.

Practically oriented courses such as design studios, workshops, or other courses that apply project-based learning methods are particularly suitable for curriculum innovation. In this respect, it could be worthwhile to study the possibility of creative 3DP tools application in the design process as opposed to just for design presentations. For example, Greenhalgh [47] noticed that developing a curricular connection between design and production may be needed to better prepare students for design-based careers. Furthermore, he observed that the iterative character of the design process would be a critical strategy in developing curricula utilizing 3DP since many students readily accepted the first model, neglecting its evident design weaknesses [47].

Furthermore, improving students' skills in using 3D software and printing technology is important. We need to understand how to better acquire 3DP skills outside the traditional educational programs and how to adapt learning from informal and formal education [46]. Additionally, the teaching approach must be customized to the students with different proficiency, experience [64,89,90], academic levels, or learning styles [91]. Furthermore, more effort should be put into creating educational support resources, such as books and other materials [48].

As observed in the literature included in this review, the application of 3DP in education could contribute to developing hands-on learning experience, problem solving, creative learning and thinking, spatial cognition [46], or increase learning motivation. However, up-to-date research does not fully explore the possibilities of the technology and its implications. Finally, it is crucial to encourage students to think of themselves as lifelong learners who are prepared to continually acquire new skills, keeping in mind the obsolescence of technology and the rapid change in socioeconomic circumstances.

4.1.2. Challenge 2: Innovating Design

The challenge for design brought by advances in 3DP technologies could be summarized in the following question: How can design processes and methods be improved using 3DP technology to increase the efficiency and quality of the production without disturbing its creative nature?

To answer this challenge, future work needs to focus on developing innovative design processes, methods, and tools and test their application on the small and large scales. In addition, using 3DP technology can support co-creation and teamwork, as they provide the opportunity to create designs in mono- or multi-disciplinary teamwork. Furthermore, 3DP technology could support better communication of ideas in the design process between participants (designers or clients) who can collaborate on the design and fabrication process. An outcome of such a collaborative approach is the generation of innovative and sustainable design processes that include fabrication intelligence, application of property-specific materials, and contribution to environmental effectiveness.

Design Process Challenges and Trends

Another interesting research topic is the study of the relation between design and design tools in the creative process. In the analyzed literature, papers on small-scale 3DP systems were mostly case studies. As a result, research on this topic is fragmented and lacks a systematized review that demonstrates how using this technology affects the design process. Furthermore, studies that assess the impact of 3DP tools on creativity are needed as well as studies on the inclusion of the technology in the early stages of the design process as a design driver. Additionally, more studies are required on design processes informed by fabrication at an early stage. Furthermore, research by design projects represents another sphere of exploration that could increase the (practical) knowledge and experience in applying 3DP technologies.

Exploring design concepts and opportunities of 3DP buildings for diverse architectural typologies, including unconventional applications—remote environments, military, and space but also extended to different planets (e.g., suggested in [19,40]) could contribute to the wider use of technology. Furthermore, the advantages of the technology could be

tested for solving global issues of providing economy housing for low-income people, local reconstruction of buildings after natural disasters such as earthquakes and floods, or military operations [13].

On the other hand, collaborative research could be done in performance-based design (PBD) to develop optimization design methods and tools. For instance, the idea of using geometry to induce structure functionality and its relationship with the construction process (e.g., suggested in [42]) needs additional research. An approach to design that asks for further studies includes material-based building automation. In this regard, Yi et al. [66] propose further development of design methods to fully automate operation, increase AM building efficiency, and enhance the controllability of component performance in different building applications.

The development of software tools for design is another work perspective. For example, Buswell et al. [74] suggested developing a tool for component design through optimization of geometry using co-simulation, coupling a model of the manufacturing process (tool path generation) with a model of the material characteristics to generate a performance model based on hardened properties and optimized design for reinforcement. Moreover, this software could facilitate manufacturing standardization by applying specific components to produce optimal configurations [74]. On the other hand, Gosselin et al. [42] proposed the future development of a tool that enables multi-scale consideration. In addition, Lowke et al. [41] suggested the development of software for design and toolpath formation. New tools should be implemented as plug-ins in design software to provide design autonomy.

Legislative Challenges and Trends

Since AM is still relatively new to the construction industry and has only a small number of completed projects, 3DP building methods are unconventional, and the applied materials have not yet undergone significant testing. Several authors have noted the lack of regulation related to 3DP constructions [13,16,19,40,51,67]. To overcome this issue, we need more studies that produce results that contribute to developing generalized standards/guidelines/codes for structural testing for each type of printing material and printing technology to ensure structural integrity. Creating a full-scale series of design criteria, construction guidelines, and standard practices for 3DP construction that reflect industry knowledge could help stimulate further research and promote implementation and expand technology in everyday use [16].

For example, Siddika et al. [19] urged the development of legislation relevant to 3DPC, while Brdarf et al. [51] focused on F3DP. Furthermore, Asprone et al. [67] proposed re-thinking conventional knowledge on reinforcement of concrete structures in terms of new possibilities offered by digital fabrication technologies and large-scale testing end-product mechanical characterization. On the other hand, more work could be done on establishing intellectual property protection for 3D design models. For example, Ning et al. [16] suggested embedding information in the spectrum and internal structures to encrypt.

4.1.3. Challenge 3: Innovating Construction Technologies

The challenge for innovating construction technologies brought by advances in 3DP technologies could be summarized in the following question: How can we develop more sustainable construction materials and systems, production models, and processes exploiting 3DP technology to contribute to creating a healthier environment and better working conditions?

The common challenges associated with using 3DP technology, especially on larger scales, are often technical. Since the introduction of 3DP in the construction industry in the late 1990s, there has been a constant trend of research focusing on the development of large-scale technology. The challenges of on-site 3DP are especially recognized as a problem with the potential for future development [75]. The second group of technical challenges

arises from the need for adequate structural properties of printing materials on large scales. Therefore, many authors focus their research on developing new materials [78,86].

More research is required to improve construction productivity, reduce labor, increase safety, and reduce the industry's ecological footprint [31]. Research efforts should also be directed towards full automation to make the process economically viable and less labor intensive. Furthermore, studies must continue to move toward large-scale experimentation and building construction to ascertain the true capability of this technology and its application in the industry [40]. In addition, other research topics could be related to lowering the resource intensity of construction, including material consumption and labor cost, and less environmental damage, such as waste and noise pollution [13].

Applied Materials and Systems Challenges and Trends

More interdisciplinary research is needed concerning material rheology, structural, and printing systems. Regarding materials, the research could concern the using multiple materials within the printing process to create a gradient of material properties [42,72]. On that line are studies on material placement, hydration control, and implementation of reinforcement or flow-induced fiber orientation [19,52,68,72]. Studies on structural properties of materials, such as anisotropic behavior under loading conditions in 3DPC [19], could also be subject of further studies. Another interesting perspective is experimentation with locally available or in situ materials to ensure effectiveness (e.g., found in expeditionary environments as suggested in [40]).

Developing new structural systems that will enable robust and reliable fabrication results could be a research goal, for example, self-reinforced systems for 3DPC elements [19]. In addition, more case studies on full-scale printed elements and their structural behavior [41] are needed. For instance, the development of building components enabled through F3DP was proposed as a research direction in [51]. In line with previous studies would be future research in advancing technology for formwork fabrication (e.g., proposed in [19] or [52]). Another promising approach is the development of optimized building elements, for example, 3D printed clay bricks, using the bio-learning methodology proposed in [88].

On the other hand, complete automation represents a final goal, and much research needs to develop methods that will facilitate fully autonomous processes. Consequently, another area of further research could involve printers' capabilities to build highly large-scale constructions and more advanced automation systems [13]. To complete automation, developing new printing systems that include effective joining systems eliminating manual assembly techniques of printed elements is needed. Such research is already proposed for 3DPC [19] or future research on the concrete casting process that eliminates the need for human intervention [52]. Schuldt et al. [40] remarked that until we develop methods to automate reinforcement placement, utilities, windows, doors, roofs, and other building elements, labor demand can only be reduced—not eliminated.

Equipment mobility issues for in situ fabrication is another topic relevant if we want to move from using only prefabricated elements. For example, further research on in situ digital fabrication was proposed in [67]. On the other hand, off-site construction (OSC) supported by innovative technologies, reviewed in [91,92], is another area of 3DP technology application that requires further research that could contribute to further developments of modern methods of construction (MMC).

The challenge of robotic interaction in 3DP building construction by 3DP is another research subject. More research similar to the one by Zhang et al. [60] that describes a system employing multiple mobile robots for printing large-scale concrete structures is needed. Additionally, an interesting perspective on construction robotics towards the unsupervised building, offered in [68], opens further possibilities for fully automated on-site fabrication.

Artificial intelligence (AI)-based solutions in the AEC industry are also a growing research focus. However, the adoption of AI techniques still lags behind the processes in other industries. Therefore, more research is needed on the optimization of design and

construction processes facilitated by systems based on 3DP and AI technologies. Moreover, smart robotics, artificial intelligence of things (AIoT), 4D printing (4DP), digital twins, and blockchains were recognized by Pan and Zhang [93] as topics for future research that could facilitate automation and intelligence in construction. Respectively, 4DP, a technology that enables 3D printed objects to change their shape and behavior over time in response to a changeable environment, is in its experimental stage, opening new research directions [94,95]. The significant advancement of 4DP from 3DP technology is its intelligent behavior in transforming configurations for self-assembly, multi-functionality, and self-repair [93].

Efficiency and Economy Challenges and Trends

Lowering costs is the goal that could be achieved by improving machines, technologies, and materials. However, a formal cost–benefit analysis should be conducted for different cases (e.g., location, printing method, printing technology, and desired output) to understand how the cost of 3D printed construction compares to that of conventional construction [40]. Economic optimization is a general trend. For example, Martínez-Rocamora et al. [80] indicated that we need research on the sequence of the necessary position of a robotic arm to execute a building layout according to its design and the machine’s range since the time for machine re-positioning can considerably influence the execution time, and, as a consequence, the economic cost of the solution. Furthermore, cost optimization could be achieved through improving technologies used in the design process. For example, the research subject could focus on how to optimize labor due to pre-processing file preparation, machinery arrangements, and post-processing cleaning (already proposed for future research related to 3DPC in [19]). Finally, mass customization is perceived as potentially one of the main advantages of 3DP in construction. In order to exploit the benefits of this approach, it is necessary to evaluate the financial performance of construction products during the whole life cycle [16].

Environmental and Societal Challenges and Trends

More research is needed to evaluate the selection of environmental indicators in the application of 3DP technology and studies on achieving sustainable employment [16]. Furthermore, to completely comprehend the environmental effects of 3D printed construction and their contribution to the circular economy, a formal life-cycle analysis looking at the sustainability aspects of the design, material preparation, construction, use, and eventual demolition of a building is required [40]. Furthermore, studies on the potential impacts of the raw materials used in the printing process and final product and the development of consistent health and safety standards (such as emission and toxicological contact control methods [16]) are needed.

On the other hand, an analysis of the tradeoffs between complete automation and human employment should also be conducted to fully understand and address the impacts of 3D printing on the construction industry [40]. Moreover, the introduction of 3DP technology into full-scale construction is recognized as having potential for speeding up the construction process and increasing workers’ safety [13,96], especially in dangerous construction environments. However, the challenge is that new technology requires a specialized workforce to operate the machines creating socio-economic problems. Therefore, education of the workforce in the usage of 3DP machines as well as the creation of simpler, more user-friendly software for machine operations are potential answers to this challenge [75].

4.2. Research Limitations

Several limitations of the study were recognized, and adjustments for these factors were made where possible. First, the authors of this study searched three major databases for the journal papers published on 3DP technologies in architecture and used the snowballing method to find additional literature. That was considered to give a more thorough

overview of the research area relevant to this study. Although this enabled the creation of more input data, bibliographic analysis was still performed on a limited sample and depended on data provided by these databases. The scope of this study should be expanded in future research to incorporate conference papers and other literature in order to provide a broader perspective on the subject. Furthermore, retrieval bias and language bias led to the potential limitation of the review. Additionally, when using the results of this research, one should be aware of the authors' bias and that a formal risk-of-bias assessment was not performed.

Additionally, the keywords contained in the articles were non-standardized. Moreover, several authors employed different variations of keywords. Finally, since several databases and snowballing methods were used for literature collection and creation of the sample, specific analyses, including co-citations, countries of origin of publications, and other more detailed links between authors and publications, could not be performed by VOSviewer due to the software limitation. However, creating a broad literature sample was valued more than producing detailed metric analysis because the primary goal of this study was to systematize and comprehend the scope of application of 3DP technology in architecture. Finally, we believe that subject-specific knowledge of authors offers context for interpreting bibliometric analysis.

5. Conclusions

This work reviews the literature on the application of 3DP technologies in the architectural discipline. First, bibliometric analysis performed on the sample of 65 journal papers showed growth in the number of publications related to the developments in 3DP technologies. Second, we identified journals in which research on 3DP in architecture is published. These journals primarily cover building and construction, engineering, and architecture fields. Third, we isolated keywords to capture the prevalent and emerging topics in the research. We also visualized keywords co-occurrence and identified three keyword clusters. Fourth, we identified characteristic themes using qualitative analysis of full texts of papers for generated keyword clusters. These themes coincide with the spheres of applications of 3DP technologies in architecture—education, design, and the construction industry. Fifth, content analysis of the complete texts enabled us to categorize 3DP systems based on the scale. Two categories—small-scale and large-scale systems—were distinguished and described in terms of differences in materials, methods, and applications. Sixth, we classified all journal papers selected for the analyses with respect to year of publication, cluster themes, and scale categories. Finally, we looked ahead to potential work directions to provide researchers with innovative perspectives, and within three major themes, we identified research challenges. Eventually, digital technologies and accelerated automation will profoundly impact how we design and construct architecture, but it is also a new system of production with economic, social, and political repercussions that necessitate further debate.

Author Contributions: Conceptualization, M.Ž. and J.M.; methodology, M.Ž. and J.M.; validation, M.Ž., J.M., R.O. and I.R.; investigation, M.Ž., J.M. and I.R.; data curation, M.Ž.; J.M., R.O. and I.R.; writing—original draft preparation, M.Ž. and J.M.; writing—review and editing, M.Ž., J.M., R.O. and I.R.; visualization, M.Ž. and I.R.; supervision, J.M. and R.O.; project administration, R.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Education, Science and Technological Development of the Republic Serbia, grant number 451-03-68/2020-14/200090. The research was done under the research lab of the University of Belgrade, Faculty of Architecture—Laboratory for Innovative Structures in Architecture (LISA).

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Documents by year

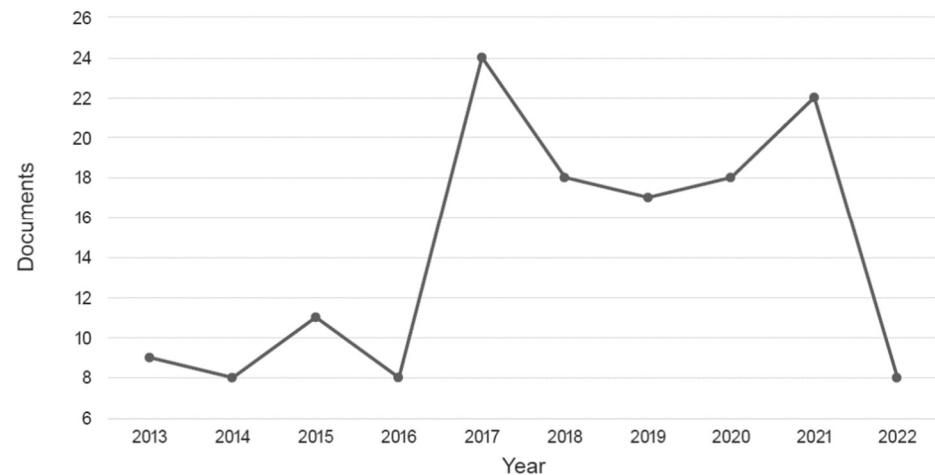


Figure A1. Publication rate of filtered articles on 3DP in architecture.

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