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Review

Additive Manufacturing Applications for Industry 4.0: A Systematic Critical Review

Samad M. E. Sepasgozar [1,*], Anqi Shi [1], Liming Yang [1], Sara Shirowzhan [1] and David J. Edwards [2]

1 Faculty of Built Environment, University of New South Wales, Sydney, NSW 2052, Australia; anqi.shi@unsw.edu.au (A.S.); liming.yang@student.unsw.edu.au (L.Y.); s.shirowzhan@unsw.edu.au (S.S.)
2 School of Engineering and the Built Environment, Birmingham City University, Birmingham B5 5JU, UK; drdavidedwards@aol.com
* Correspondence: sepas@unsw.edu.au

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Abstract: Additive manufacturing, including 3D printing (3DP), is one of the critical pillars of Industry 4.0 and the next construction revolution. Several countries, including China, have utilized 3DP on larger scales or real projects. However, reviews of the lessons learned from previous large-sized practices of 3DP utilization are scarce. This paper presents a few practical applications of implementing 3DP over the past decade and suggests a direction for future research work. Recent publications on 3DP practices are systematically reviewed using an interpretivist philosophical lens, and more specifically, the nozzle characteristics are focused upon. The Scopus and China National Knowledge Infrastructure (CNKI) journal databases are utilized, resulting in the examination of 54 English and 62 Chinese papers. The selected practices from Mainland China, Hong Kong, Taiwan and Macao are considered for this review. A content critical review approach is adopted, and the identified papers are critically reviewed. These papers reported key challenges and advantages from their reported practices, such as limitations in aggregate sizes, nozzle sizes, standards, post-occupancy satisfaction, final product quality, productivity challenges and other associated risks. The paper reports upon prominent limitations and signposts directions for future investigations.

Keywords: 3D printing; additive manufacturing; building information modeling (BIM), laser scanner; contour crafting

1. Introduction

3D printing (3DP) has developed substantially over recent decades and is synonymous with intelligent and efficient technology, the applications of which are myriad in developed economies internationally. These applications traverse the diverse fields of science, including biomedical, aerospace and engineering. Yet compared with the exponential growth of applications and further development of 3DP technology in other industrial sectors, its implementation within the construction industry only accounts for 3.1% of the 3DP application market [1]. This slim market share is somewhat enigmatic given that the global annual revenues of the construction industry are valued at $10 trillion, which accounts for 6% of global GDP [2]. Moreover, 3DP offers a viable solution to many major recurrent issues that doggedly persist within the sector, including the need for affordable homes, augmenting quality control and mitigating cost overruns. While there are many papers that promote a 3DP approach for on-site construction, industry readiness remains low, thus precluding its widescale adoption. For example, Tahmasebinia et al. [3] note that while 3DP was introduced to the construction sector in the 1980s, its applicability and relative advantages have only recently been recognized by practitioners who note the significant challenges its adoption poses. This paper attempts to identify and delineate these challenges and define necessary directions that future research should take in order to address them. These objectives will be achieved by conducting a systematic review of extant literature, using different terminology and assumptions. To ensure consistency throughout the paper, definitions relevant to 3DP are summarized in Table 1. Tahmasebinia et al. [3] define 3DP technology as a useful technology for developing construction automation and increasing the sustainability practices in this field. Technology per se refers to the method, process, technique or knowledge, here related to 3DP. 3DP is one of the recommended technologies for implementing the Industry 4.0 concept in the construction context, which refers to developing or implementing the relevant tools, mechanisms, materials, hardware and software [4]. Industry 4.0 encapsulates the coalescence of existing digital technologies and techniques in order to build a resource-efficient, automated or smart construction process [4,5]. By embracing advanced automated digital technologies such as 3DP, forward-thinking practitioners and academics aspire to address the aforementioned challenges posed, which have their antecedents founded within human intervention (viz: acts or omissions).

Table 1. Summary of definitions for consistency throughout this review.

Concept	Definition and Associated Key Words
Additive manufacturing	A process utilizing an industrial fabrication technique to create solid objects (typically layer upon layer [6]) by using computer-generated models [7] in the absence of human intervention [8].
3DP, 3D print, 3-D print, 3D printing or 3D concrete print [9]	A production technology [10] sequentially laying down layers of material until the envisaged form of the object has been developed [8] using digital information. Reduces lead time and cost in construction and increases sustainability [3,11].
3D scanner [12]	Provides massive point clouds to create precise 3D representations of objects and offer dimensional data from construction objects for 3D modeling [13]. Light detection and ranging (lidar) [14], mobile and terrestrial laser scanners [15], drones.
Construction technology	Refers to materials, equipment, technical methods, novel construction operation processes, unique formworks, knowledge and tools or any digital hand tools, hardware, heavy equipment or machines [10]. Cranes equipped with programmable system, autonomous haulage system, global positioning system (GPS) and radio frequency identification (RFID).
Industry 4.0 (the Fourth Industrial Revolution) [4]	Refers to the use of advanced technologies for mechanization [3,5], which can be based on a network of automation, self-configuring, knowledge-based, or sensor-based [16] systems, including the use of 3DP in the production.
Technology adoption	How companies make a decision to accept and utilize technology at the organization level and whether the technology and similar implementation methodologies can be equally successful in any construction project, due to the unique nature of projects or customized technology, known as the ”adoption paradox” [4,17].

Note: Five different groups of construction technologies and some of the associated terms are discussed by Sepasgozar and Davis [10].

3DP is associated with different key terms such as liquid, sheet or powder bed additive manufacturing (AM) technology [18], and fused deposition modeling (FDM) (such as D-shape, contour crafting (CC) and concrete printing) [19], selective laser sintering (SLS) and selective laser melting (SLM), another powder-based AM technology used in different countries [18]. Using these technological solutions, a number of prominent advancements and applications of 3DP have been employed in both industry and practice. For instance, Huazhong University of Science and Technology (HUST), China, developed a 3DP system for large objects, which solved previous restrictions on not being able to print buildings larger than 1000 mm on SLS and SLM systems [20]. The SLS scales up to

$1400 \times 700 \times 500$ and $1400 \times 1400 \times 500$ mm^3, and the SLM system enlarges the project dimensions to $500 \times 500 \times 400$ mm^3 [20]. The CC variant of FDM is the most widely accepted by the Chinese construction industry and has been applied to the construction of many successful structures and buildings. For example, in 2014, China's Winsun Decoration Design Engineering Co. achieved a tall 3DP building and completed ten houses within 24 h in Jiangsu, China [21]. ZhuoDa Group accomplished a ready-made modular of a 3DP house by a LEGO brick technique that theoretically resists an earthquake of level nine on the Richter scale, while HuaShang Tengda managed to create the world's first villa by a custom-built 3DP system, which conceptually withstood a level eight earthquake [21]. In a further development, Winsun combined an aquaponic system with 3DP to achieve sustainability [21]. The first 3DP office was built in Dubai within 17 days in 2014 [21]. A challenge that limits the implementation of 3DP is the lack of controllability of the extruded geometry of printing specimens, which leads to the deformation of the printing material and other quality issues [22]. The structural stability of the printed specimens is mainly attributed to pumpability, extrudability, buildability and open time [23–25]. However, Shakor et al. [26] experimentally determined that different shapes of nozzle lead to different intercepting shocks, which influence the printability, shape and flowability of the slurry. Roussel et al. [27] reached the conclusion that in the process of printing, the distance between the nozzle and the previous layer limits the flowability of printing material, with a smaller distance resulting in a locally compressed and deformed filament. Contextualized against this prevailing background of 3DP opportunities and limitations, this paper seeks to conduct a systematic review of contemporary literature on this advanced technology, with specific focus on nozzle shape and size. The work is structured into three parts: first, the research method is presented; second, selected papers are reviewed and analyzed; and third, the limitations of current literature are analyzed, and future directions are delineated.

2. Research Method

To evaluate 3DP practices, two primary databases were selected to conduct interpretivist research, namely Scopus and China National Knowledge Infrastructure (CNKI). Scopus is a high-quality international database and CNKI is an extensive database that includes Chinese scholarly papers. Different keywords, such as building information modeling (BIM) [28], scanner [15,29], and 3DP, were used to identify relevant papers within the construction and structural design fields. Figure 1 illustrates the outline systematic review process, keywords and the exclusion or inclusion criteria, whilst Figure 2 presents the methodology used for collecting, selecting and filtering relevant articles based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach [30], and similar systematic reviews in the construction field [31,32]. The bibliographic analysis was used since it shows who contributed to the topic and how the topic has evolved over time [33,34]. A set of keywords was used in combination with 3DP to review how these technologies work together and identify the existence of potential applications. Analytical network maps of co-occurrences of keywords were generated in order to visualize the main concepts in the 3DP literature and their possible evolutions or inter-relationships. This is a common and useful practice that is used for other topics in construction [35,36].

Conference proceedings, trade publications, book series, the publication year 2020 and medicine, physical and astronomy, biochemistry, genetics and molecular biology, agricultural and biological science, pharmacology toxicology and pharmaceutics, immunology and microbiology, were excluded after manual processing, and 116 papers were selected to be reviewed. The search keywords are indicated in the Appendix A.

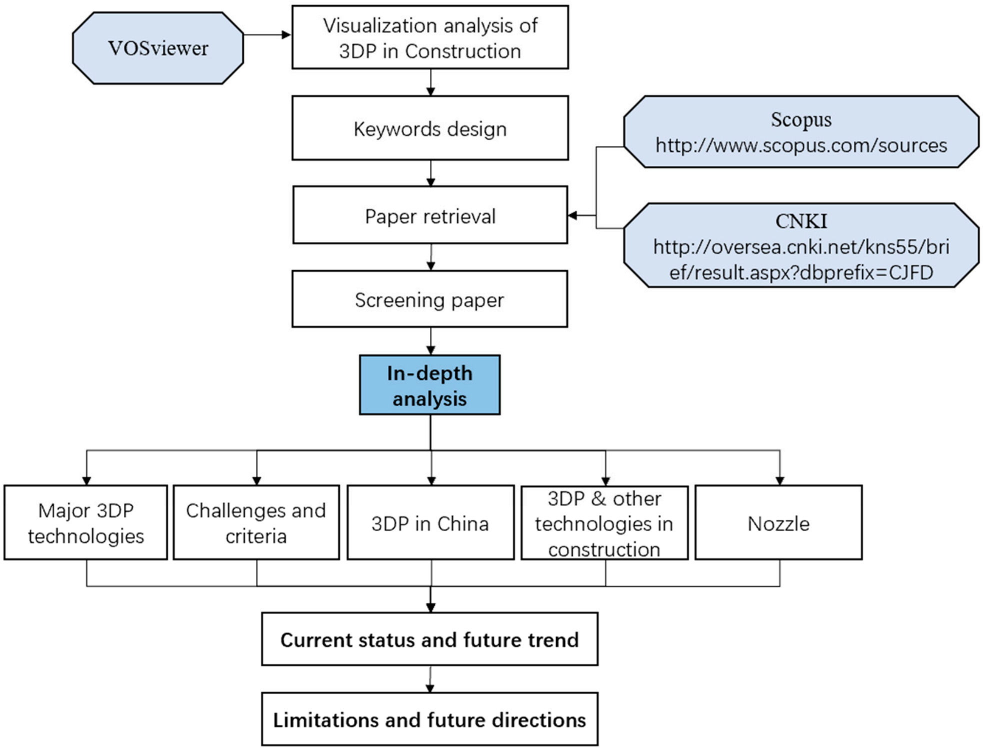


Figure 1. Research flowchart, including the main tasks of the present systematic review process.

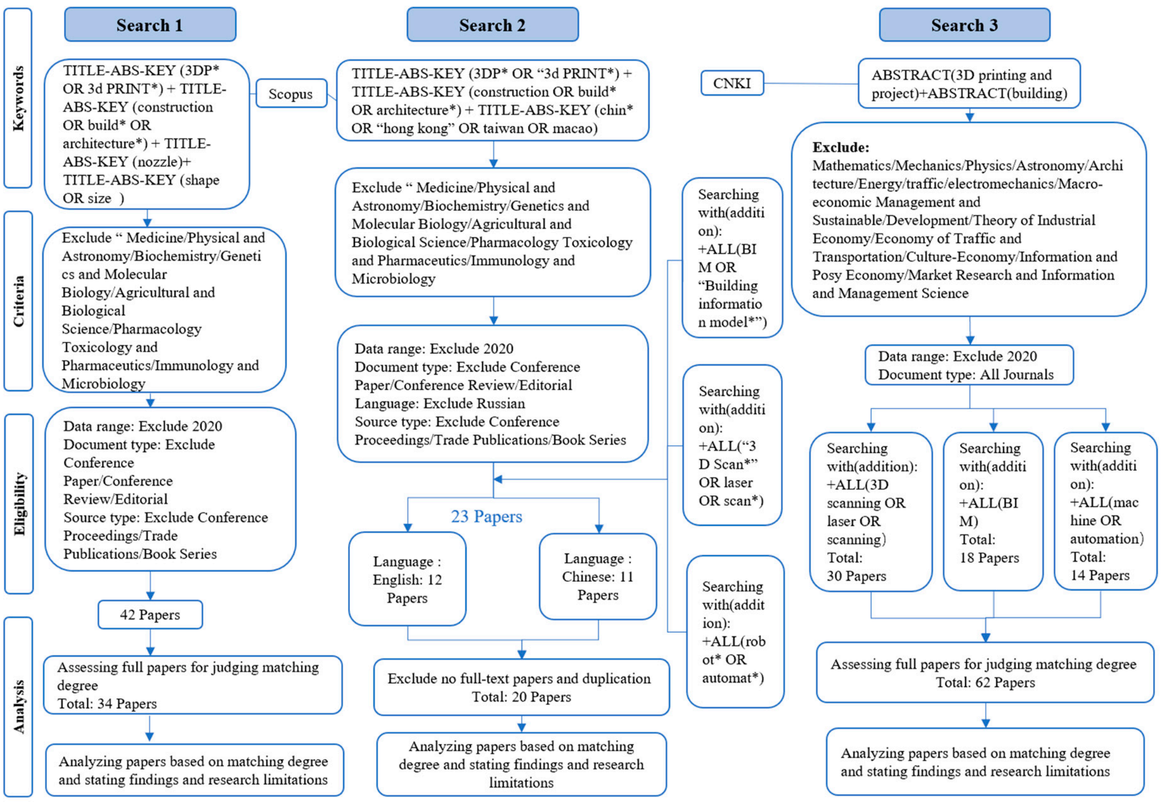


Figure 2. Flowchart for identifying relevant papers in Scopus and CNKI, based on preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach.

3. Results

In order to identify the current status of 3DP in construction, in terms of co-occurrence of keywords, a networking approach was used, which incorporated recent papers from the three-year period 2018 to 2020. Figure 3 shows the network of keywords limited to journal articles within six relevant subjects: engineering, computer science, business, decision sciences, social sciences, and energy. The string was considered based on the Search 2 strategy (refer to Figure 1): Title-Abs-Key ("3DP" OR "3d PRINT *") AND Title-Abs-Key ("construction" OR "build *" OR "architecture *"). VOS viewer was used to identify keyword hot topics of 3DP research in the construction context based on the co-occurrence of keywords. Figure 4 shows fractional analysis of the co-occurrence network, which mainly relates to "mechanical properties", "microstructure" and "material science". Figures 3 and 4 show the key focuses in this area, including the links of 3DP concept with "tensile strength", "compressive strength" and "mechanical properties"; the mechanical properties of the material are the bases of 3DP implementation in construction. Thus, researchers have conducted research of 3DP in construction from the microscopic and macroscopic perspectives, respectively. The keywords "shape optimization" and "process parameters" were also connected to "3d printing" [37–41]. This connection shows that the optimization of printing parameters and specimen shapes are still the key focus of future research [42–49]. Figure 3 shows the appearance of the "robotics" key word [50–53] and Figure 5 shows the co-occurrence of key words. This means that the construction phase will be handled by robots rather than humans.

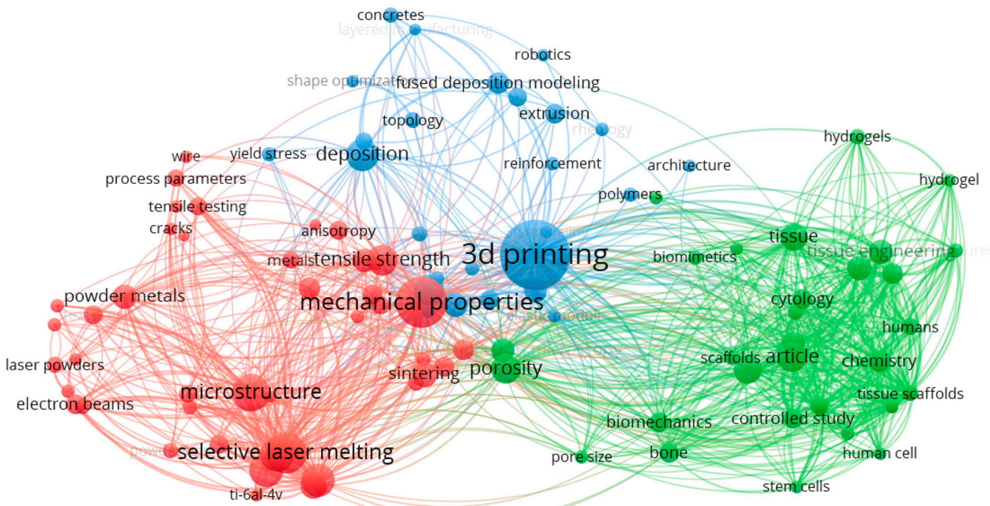


Figure 3. Co-occurrence analytical map of keywords generated based on Scopus data set. Note: the minimum cluster of 40 is considered and three clusters include 109 keywords among 2321 papers.

Figure 6 reflects the distribution of each topic of paper in the English database Scopus (a) and the Chinese database CNKI (b).

The results indicate that Scopus contains more papers related to "3D scan or laser or scan *" compared to "BIM" and "robot or automate". However, in the CNKI database, the number of papers related to "BIM" or "robot or automation" is greater than "3D scan or laser or scan *". Thus, this research result indicates that in Chinese articles, 3DP is more focused on "BIM" and "robot or automation", highlighting a large and unexpected difference in research topic between China and the English-speaking world.

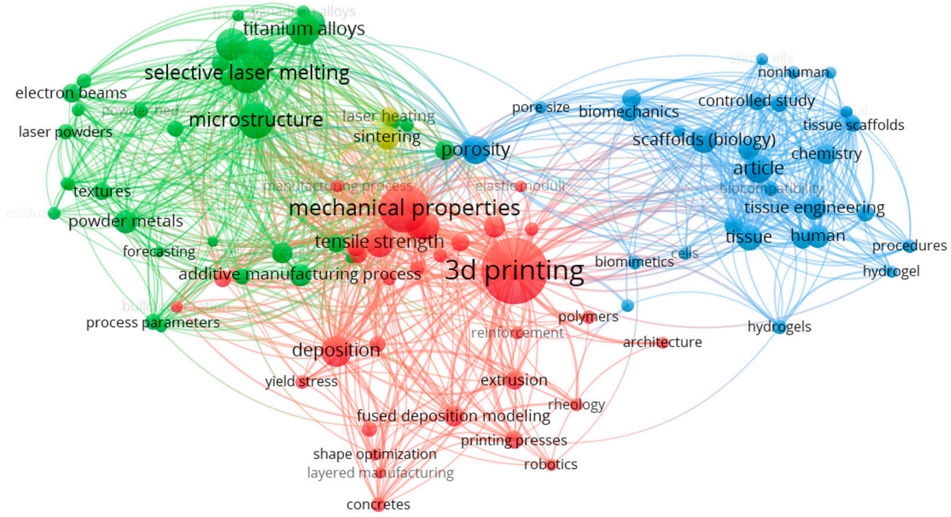


Figure 4. Fractional analysis of the co-occurrence network.

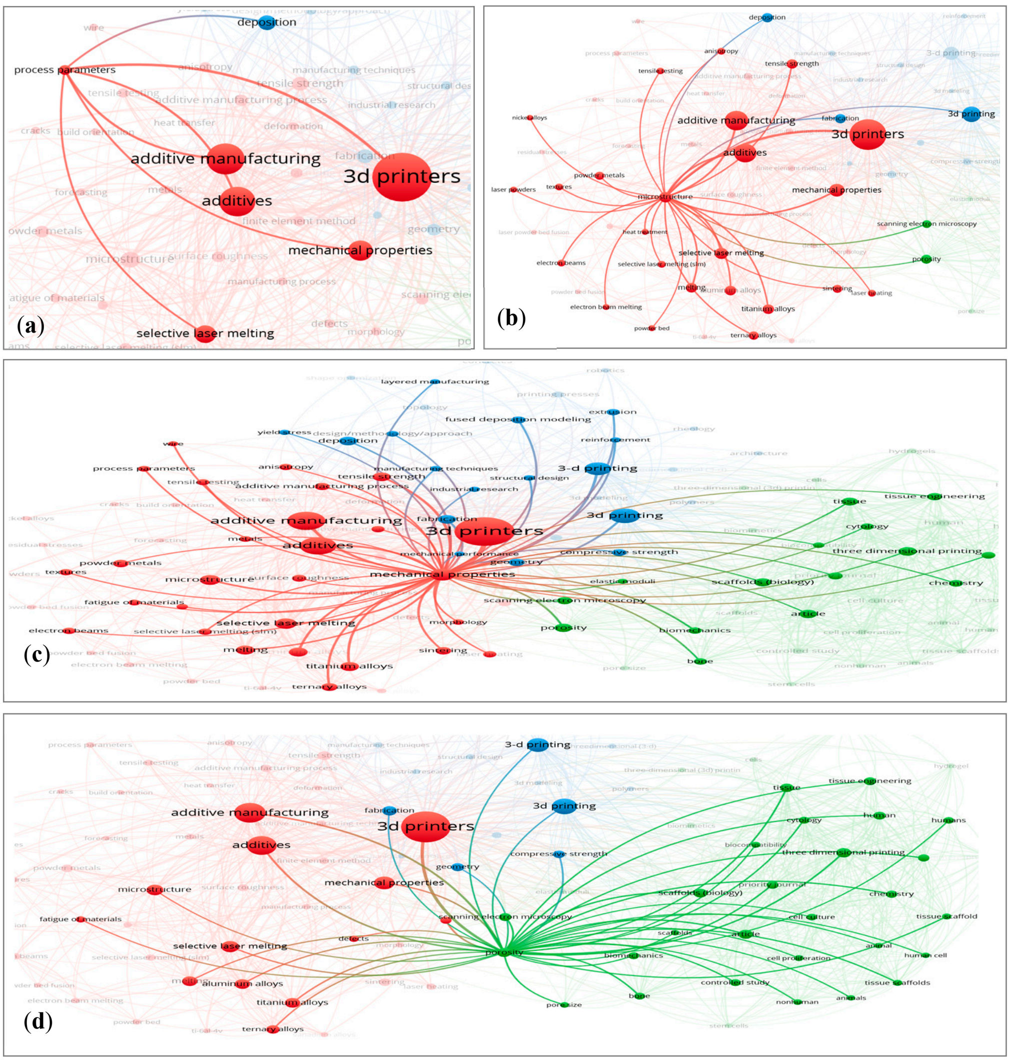
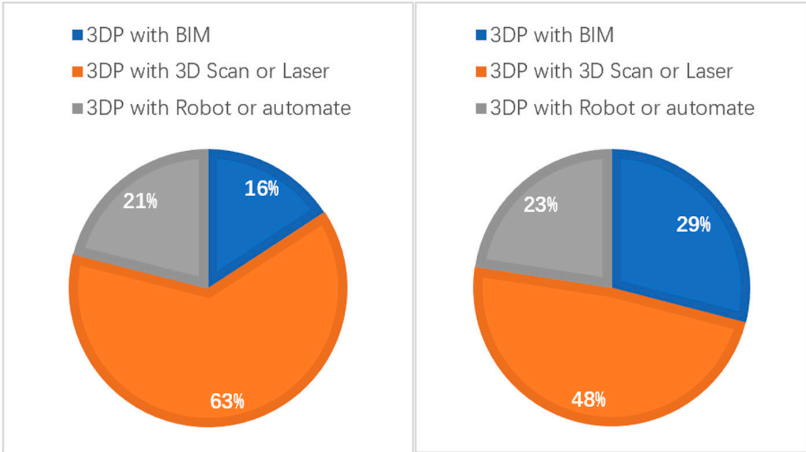


Figure 5. Co-occurrence analytical map of selected keywords created on bibliographic Scopus data for each group of keywords within and outside their individual groups: (**a**) process parameter network map; (**b**) microstructure network map; (**c**) mechanical properties network map; (**d**) porosity network map. Note: the minimum number of co-occurrences of keywords was 40, with a minimum strength of 0.



(a) (b)

Figure 6. The distribution of papers in different topics: (**a**) English database Scopus; and (**b**) Chinese database CNKI.

3.1. Content Analysis

Tables 2–4 contain detailed information for each 3DP article that was researched from Scopus. In these tables, the classification is based on the relevance of the article and China's 3DP applications.

Table 2. Selected papers from the Scopus database related to general concepts of 3D printing (3DP) methods, including selected cases in China.

Aims and Objectives	Method	Limitations	Outcome
Examine three common largescale 3DP systems and the main challenges they face [19].	Chinese Winsun Company used CC to create a five-story apartment; ten houses built in Shanghai by gigantic 3DP within 24 h; 3D printed five-story apartment in Jiangsu Province, China.	The 3DP size limited the components' dimensions; the reinforcement implementation; lack of relevant standards and testing methods for new cementitious material.	Developed some criteria, including shrinkage, for producing an optimized cementitious mixture.
Discuss the ownership and legal issues of 3DP [54].	Feng Xu's Vulcan project, the largest 3D structure in the world.	Copyright issues as it is too easy for stakeholders to modify and incorporate.	In China, Philip Yuan and Hao Meng introduced the robotic platform.
Develop a methodology that combines three-dimensional (3D) scanning and cement mortar-based 3DP [55].	Combine 3D scanning and cement mortar-based 3DP. The cup-shaped individual plinth is damaged and replicated through 3D scanning, remodeling and re-construction.	New approach for the materials; less control on mechanical motion and a precise and flexible nozzle; lack of the restoration modelling algorithms for alternative or missing elements.	This methodology is a novel approach for replicating a heritage decorative element as the labor cost is expensive and the process is fussy.
Develop an SLS and SLM system for large objects [20].	A multi-layer flexible preheating system according to self-adaptive fuzzy control technique. A non-uniform temperature field is created by the single-large preheating system.	Material limitations.	Suggests a material with high mechanical properties, which is high impact polystyrene. Evaluates the other suitable material for SLS, a mixture of polyamide (PA) and reinforcement particles.

Table 2. *Cont.*

Aims and Objectives	Method	Limitations	Outcome
Virtually reconstruct the Fisher Island Pagoda Lighthouse (China): repair the historical buildings [56].	Revit used to rebuild a 3D virtual construction for a 3D printer, using the lighthouse at Penghu, between Xiamen and Taiwan.		Shows 3DP and Revit have benefits for historical building replication.
Size challenges and structural performance [57].	According to experience, increase the column 10-fold. It uses the facade of Arachne designed by Lei Yu, a Chinese architect (Foshan, China, 2017) as an example.	Size affected structural performance.	3DP is more suitable for small-scale and customized structures until 2017.
Develop a new type of Tial alloy by selective electron beam melting (EBM) [58].	Evaluates SLM and EMB for manufacturing the metal material.	The material preparation for the Tial alloy; the microstructure evolution process of EBM samples during heat treatment.	Suggests SLM and EMB to be used for manufacturing the metal material.

Table 3. Selected papers from the CNKI database related to general concepts of 3DP methods.

Aims and Objectives	Method	Limitations	Outcome
Evaluate SLS, SLM, SLA, EBM and FDM methods [59].	Discusses a case study of Oakland Bay Bridge for the earthquake in San Francisco.	Limited material; size; durability of the 3DP; lack of estimation, cost control and benefits maximization when combined with the conventional approaches.	Contribution in the connecting point between components; presents a large casting mold printing manufacture and earthquake resistance.
Decoration application using BIM and 3DP [60].	A case study to conceal fire-hydrant box stone door for a theatre project including scenario simulation.	Limitation to printing object size; higher accuracy requires more time; limited materials.	Successful experiment for the decoration finishes of complex units including model sandboxes.
Principle of 3DP: demonstrate 6 ways of 3DP, with benefits and limitations [61].	A 10-story building developed by Winsun company.	Limited materials; accuracy; lack of required standards.	Presents a cost-effective benchmark, suitable for rapid fabrication of small batches of complex units.
BIM 3DP integration for a case project of Urumqi International Highway-railway [62].	Integrates different tools including Rhino, Catia, Revit, the 3D laser scanner and total station, RealWorks and Naviswork.	Interoperability and lack of functionality in BIM and other tools.	Successful use of BIM with 3DP for design, production, constitution and management phases.
Introduced a multi-head printer and developed a self-climbing 3D printer [63].	A 10-story building, and the VULCAN created by LCD in Beijing's Parkview Green retail center.	Problem with 3D printing, the building height and low outcome caused by the single printer head-solved in this paper.	Reports successful practice with high safety level; presents a cooperative path plan of multi-printhead printing.

Note to table: SLS: selective laser sintering; SLM: selective laser melting; SLA: stereolithography; FDM: fused deposition modeling; LCD: Laboratory for Creative Design.

Table 4. Selected papers from the CNKI database related to a detailed analysis of general concepts of 3DP practices, including structural and architectural examples.

Aims and Objectives	Method	Limitations	Outcome
Analysis of the utilization of pre-fabricated housing system projects with PC-steel and 3DP [64].	Self-supporting floor slab with a space truss support system in the middle of the slab, reducing the slab weight.	Material and reinforcement limitations.	Presents an application for hollow concrete structural units (volumetric modular), such as the entire bathroom or kitchen, which can enhance the flexibility of house space.
Develop architectural elements and evaluate limitations [65].	Develop a self-insulating wall and install the pipes. The alternative method is to print the wall with two-sided formwork and pour concrete.	Limited aggregate size due to nozzle size; limited size of the 3D printer; interoperability issue; difficulty in printing doors, windows and pipes.	Evaluates an architectural practice and presents a large-scale 3DP at Zhangjiang Qingu Science and Technology Park, China.
Evaluate the CC method for both 10 and 6-story buildings in China [66].	Evaluate CC methods by hanging a nozzle on the crane and moving in the X and Y directions.	Limited material type; software issues, hardware facility; lack of relevant standards.	Discussion around earthquake resistance and the ”ink” used for achieving high strength and lightweight concrete.

3.2. Major 3DP Technologies

Tao et al. [59] review three different 3DP technologies. The first comprises SLS, SLM and SLA. The SLS and SLM mechanisms are layer by layer, and a laser beam scanning powder generates every single layer [67]. The second technology is EBM, which is similar to SLM, but EBM works in a vacuum environment and uses the metal powder under an electron beam. EBM products are smoother with high-quality performance [68]. The last approach is FDM, which involves the deposition of layers of extruded material [69]. FDM (and its variant CC) are discussed in this paper as they are widely used in the Chinese construction industry. Table 5 presents some information for 3DP technologies with the material information and working principles.

Table 5. Further 3DP technology information from sample papers [61].

Method	General Information
Material jetting (MJ) [61]	Like the inkjet printing approach, the liquid photopolymer or waxy material is selectively sprayed through the nozzle.
Binder jetting (BJ) [61]	The adhesive is selectively sprayed onto the powder base layer through the nozzle.
Stereo lithography appearance (SLA) [61]	Selectively scans liquid photopolymer with a certain type of light source and solidifies quickly, such as AM created by 3D system companies.
Fused deposition modeling (FDM) [61]	Under certain pressure, the filamentous polymer materials are softened by a heating nozzle just above melting point, then stacked to form a 3D structure.
Selective laser sintering (SLS) [61]	Like BJ, but SLS uses laser or electron beams.
Directed energy deposition (DED) [61]	Uses a laser or other energy to simultaneously melt the “ink”, solidify and stack to form 3D structure.

3.3. Development and Challenges of Largescale Printing

Ma et al. [19] review three common largescale 3DP systems (D-shape introduced by Enrico in 2007 [70,71]; CC created by Khoshnevis in 1998 [72]; and concrete printing used globally in the construction field) and three of the latest 3DP techniques (Stone Spray [73]); cellular fabrication technology [74]; and BigDelta [19]. Their applications and limitations are stated in Table 6 [19]. There is no size specification of largescale structure printing. Regarding the SLS and SLM systems, they could not accept a dimension > 1000 mm before 2014 [20].

Table 6. Summary of largescale 3DPs used in the selected dataset of papers.

3DP	Applications	Limitations
D-shape: Enrico [70] in 2007, sand, salt, and inorganic binding agent [19].	Applied on very largescale structures [75]; allowed faster construction for the army, such as support and hospitals. It has a high printed performance due to the narrow and precise nozzle.	The approach of deposition may determine the printed dimension.
Contour crafting: Khoshnevis in 1998 [72], materials have a shorter setting time and low shrinkage [19].	Applied on very largescale structures through a multi-axis robotic arm. The printing process is very fast, allowing printing on-site; the faster print speed is due to the single large nozzle, which is applied on low printing performance and large thick layer.	It cannot print roof and window at the same time.
Concrete printing, material: cement mortar [19].	The alternative approach of counter-crafting: better for complicated or freeform structures as no need for formwork and subsequent vibration. The rapid printing speed depends on the individual large nozzle, which is applied to low printing performance and large thick layer.	The approach of deposition and the mechanical fabric determine the printed dimension.
Stone Spray—a robotic 3D printer (Institute for Advanced Architecture of Catalonia (Spain) 2012) material: sand and soil with environmental adhesive [19].		
Cellular fabrication technology (C-Fab): Platt et al. in 2013 [19].	Used to produce sustenance construction. More suitable for largescale structures.	
BigDelta: 12m × 6m gigantic 3D printer, used below 100 W of power [19].	Used to print sun-dried brick building on-site with environmental materials, such as clay, water and straw and soil. It also used a lift linked with a 3D printer to deliver the material.	

Ma et al. [19] highlight that largescale 3DP is cost-effective, efficient at reducing construction waste, suitable for freeform buildings or complex structures, sustainable and capable of providing a higher safety level on construction sites. There are three main challenges: the limited scale of the produced components, reinforcement issues and voids available in concrete. Figure 7 shows a few models created in the experiments conducted for the present paper, and they confirm that there are some deformations and issues in the final products using different materials such as plastic and clay [8]. The waste of material has also been observed in these experiments (see Figure 7), but this might be much less than in conventional construction methods.

Fok and Picon [54] report on the standard and copyright issues of 3DP practices. In China, Philip Yuan and Hao Meng introduced the robotic platform as one method to solve the issue of open-source architecture. Open-source benefits are easy modification and coordination between stakeholders, but it is also easy to misunderstand the responsibility [17]. Xu [76] indicates that the copyrights between any two counties are different and, as such, this constitutes a significant potential issue of 3DP.

Moreover, many papers indicate that prevailing standards or copyrights are a significant limitation for China's 3DP development. Yu et al. [77] state that existing criteria are no longer applicable. Yu. [61] and Su et al. [66] state that standard specification problems should be considered as barriers.

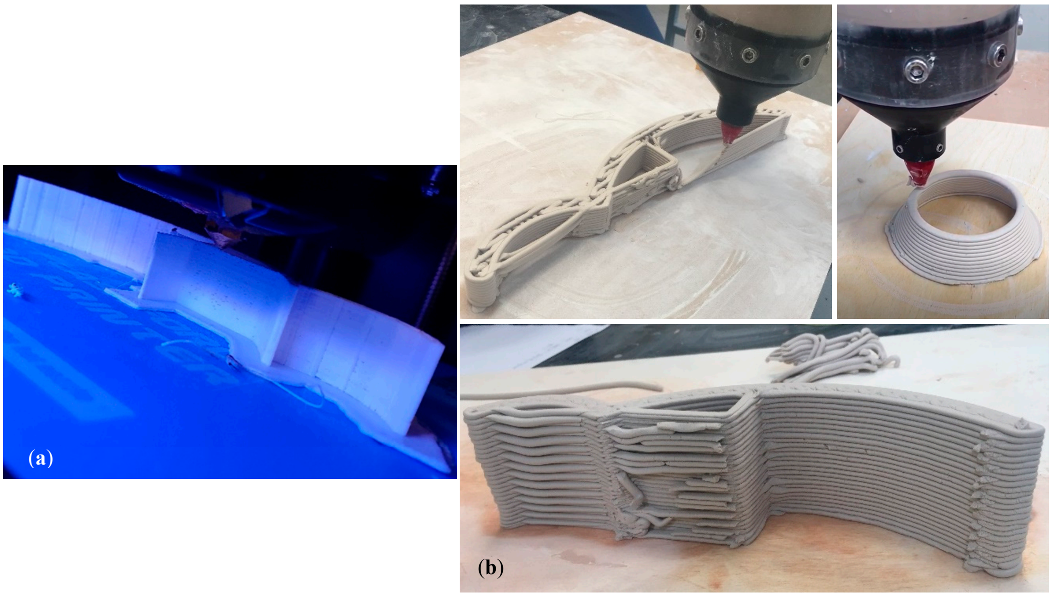


Figure 7. 3DP models created at the laboratory by the investigators: (**a**) using plastic materials; (**b**) using clay (source: authors).

3.4. Criteria of 3DP Material Discussed in the Literature

The material challenge is the primary barrier to the adoption of 3DP in China and worldwide. The extant literature reveals that there are no united criteria for material but provides a reference based on the experiments conducted.

Ma et al. [19] develop some criteria for producing an optimized cementitious mixture, including shrinkage, extrudability, flowability, setting time, buildability and mechanical properties (refer to Table 7). For example, the control of extrudability tends to achieve a round shape, smooth grading and tiny particles, which is akin to self-compacting concrete. Figure 8 shows examples of deformation and issues in the final product, as part of experiments conducted by Shi et al. [78] and Tahmasebinia et al. [3].

Table 7. Summary of criteria discussed in the literature and examples from the sample.

Control Criteria	Definition	Examples
Shrinkage	The material deforms during the coagulation process, which causes dimensional deflection [79].	In specimens with the structural nano-synthetic fiber around 0.26 vol %, the crack area reduces 36% from the original [19].
Extrudability	The workability of material to be moved out from the nozzle [80].	The optimized mixture proportion is 3:2 sand–binder and mixes with 70% cement, 20% fly ash and 10% silica fume [19].
Flowability	The ability of the material to spread from the nozzle; it should be easy to pump out [71].	Varies in different experimentations. The rate observed varies from 1.1 to 1.4 cm/s for superplasticizer rates of 0.14%, 0.28%, 0.30% and 0.35% [19].
Setting time	Extended setting time requires extrudability and flowability, but should not be too long due to buildability requirements.	Six different retarders are tested. The sodium tetraborate is optimal, and the critical point is from 0.1% to 0.3% [19].
Buildability	Stiffness of material to lay down without collapsing [80].	The critical point of viscosity modifying agent (VMA) mixed in the paste is from 0.025 to 0.075%. The adhesiveness of the mixture at 0.075% is over four times stronger than at 0.025% [19].
Mechanical properties	These relate to compression, strength, flexibility and physical properties.	The specimen with fiberglass-reinforced plastics (FRP) can achieve 31.5 MPa maximally, as 1729.0% times that of unreinforced specimens [19].

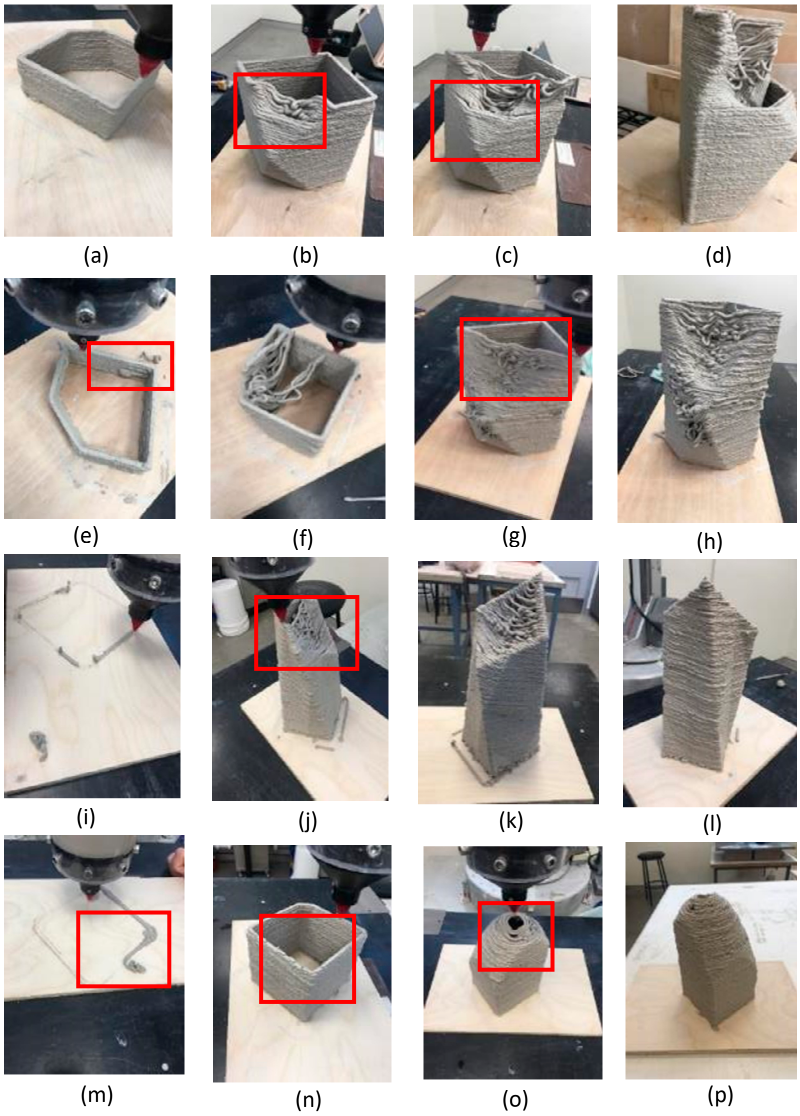


Figure 8. Architecture models made of paper clay: (**a**–**d**) Model 1 100%; (**e**–**h**) Model 2 100%; (**i**–**l**) Model 3 100%; (**m**–**p**) Model 4 100% (source: authors).

Additionally, Hager et al. [81] demonstrate that sulfur concrete would be the 3DP material as it contains sulfur and aggregates. It obtains the required strength after cooling between 130 and 140 °C near the melting point. There are claims that sulfur concrete might be the material used on Lunar as well.

3.5. Environmental, Social and Economic Benefits Reported in the 3DP Database

Zhang and Su [65] state that China's labor resources are in short supply and the construction industry contaminates the environment, intimating that changes in response are inevitable. In 2013, China's 3DP was involved in the national development strategy project and consequently, many big cities, such as Chengdu, have launched 3DP development.

Tao et al. [59] discuss 3DP as a high-level accuracy manufacturing process that can be controlled to within 0.3 mm. For instance, the project SD 6000/7000 of 3D Systems can reach 0.025 to 0.05 mm, suitable for major products' requirements. 3DP is highly efficient as no mold is required during the process, but customized products can be created using a diverse range of materials. Therefore, 3DP can control the financial budget while maximizing customer satisfaction and is an eco-friendly construction method.

Zhang and An [82] report the advantages of 3DP as materialization, improved safety and enhanced high-efficiency, which reduces environmental impact by reusing waste materials. Figure 9 shows the results of the thermal and humidity analyses of the models created in the laboratory by the student author of the present paper. This type of analysis is important for predicting the post-occupancy satisfaction of the 3DP models, as well as the structural analysis of the item created, by measuring the moisture lost per day. There is a need to measure all the thermal, sustainability and environmental indicators of the items created by 3DP in different contexts and climates. Zhang and Su [65] confirm that 3DP saves energy and provides a long-life cycle because conventional construction is a complicated process that is labor and equipment-intensive. In comparison, 3DP can be controlled by intelligent operation and cloud-based servers.

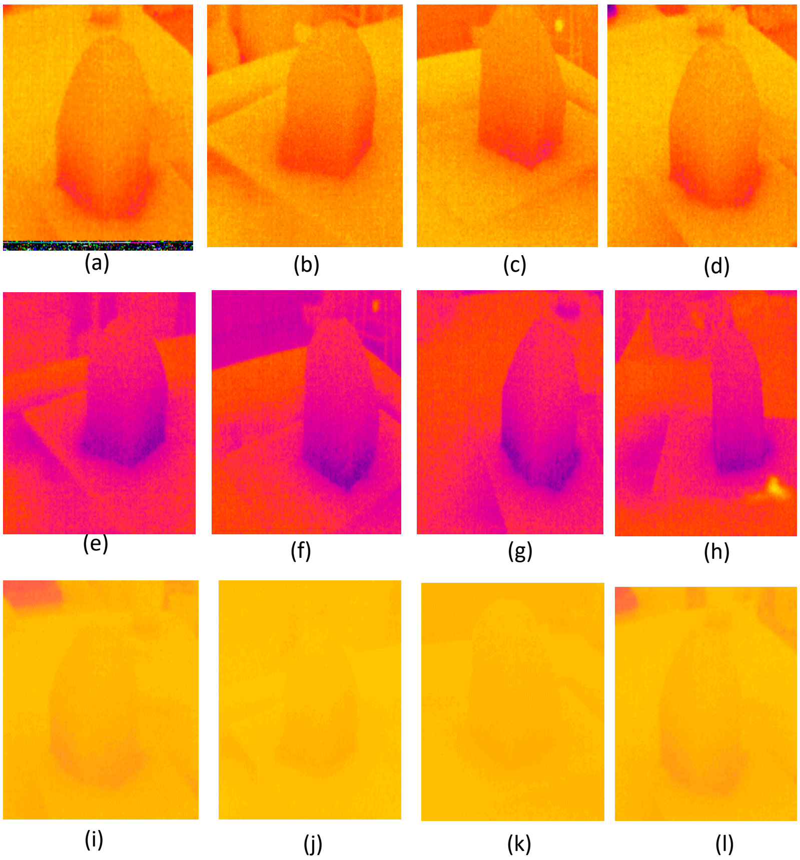


Figure 9. Model thermal and humidity analyses in the laboratory: (**a**–**d**) model thermal image 24–28 degrees; (**e**–**h**) model thermal image 25–29 degrees; (**i**–**l**) model humidity, 65–66% rh with 28 degrees using a thermal scanner 875-2i (source: authors).

Yu [61] demonstrates that 3DP technology could reduce construction material usage by 60%, lower labor by 80%, shorten construction periods by 70% and reduce construction costs by 30% per square meter. The benefits of 3DP are palpable and include its integration with modern information technology, computer-aided manufacturing technology, new material technology and mechanical technology. Design and manufacturing are highly integrated, and a complex structure does not limit 3DP as it is an automated process. Yu [61] reiterates the benefits with regard to the customized, efficient and diverse materials that can be used, but also refers to quality control and assurance and the rapid fabrication of small batches of complex units that are suitable for China's market. Yu et al. [77] demonstrate the same benefits for 3DP but also refer to a shorter payback period on investment and lowering of labor intensity, thus alleviating labor shortages in China [65].

Su et al. [66] reiterate the same benefits and highlight that earthquake resistance is theoretically excellent because the 3D printer prints entirely, and the "ink" used is high-grade concrete, which can achieve high strength whilst simultaneously being lightweight [66].

3.6. Review of Industry Practices

Su et al. [66] state that the Chinese construction industry began to accept 3DP technology due to the CC method improving the performance of construction, as it hangs the nozzle on the crane and moves in both X and Y directions. The finished product has higher strength and excellent surface finishes using this method [66]. Table 8 shows a summary of selected successful projects using 3DP technology. The first case study (ID 1) presents a large-sized project comprising ten houses with a gigantic 3D printer (150 m × 10 m × 6 m). This project used recycled waste materials or natural stones from mining sites that were processed before use. The walls were printed with some room for beams and columns, steel bars were inserted, and spaces were filled with the required insulating materials. The second project (ID 2) presents a five-story apartment in Jiangsu Province, China, which in 2014 was known as the world's tallest 3DP structure [83]. The diagonally reinforced printing process was used in the walls and other parts of the building to form a hollow section for insulation; this was off-site manufactured in the factory [81]. The third project (ID 3) presents a two-story villa constructed by using the factory-manufactured LEGO brick approach, which was assembled on-site in three hours using a mobile crane [84]. The fourth project (ID 4) presents a two-story villa built in the Tongzhou District, Beijing, within 45 days [85]. The formwork used traditional reinforcements and installed plumbing pipes [86]. A forked nozzle was used to extrude the double layers of concrete simultaneously [86]. The fifth project (ID 5) created the Classical Gardens of Suzhou, Shanghai, and was completed in two months at a competitive rate. The walls were designed as hollow structures to save materials and money, reduce the weight and grant the place insulation [87]. The sixth project (ID 6) shows an office printed in Dubai via a joint venture contract with a specialized company in China [88]. Table 8 summarizes these selected projects in China.

Table 8. Summary of selected 3DP practices.

Case/Year of Practice/Company	3DP Technology and Details	Material	Design Complexity
(1) Ten houses in Shanghai by gigantic 3DP within 24 h/2014/Winsun Company [19].	Gigantic 3D printer of size 150 m × 10 m × 6 m; CC (method) [19].	High-grade quick dry cement and glass fiber [19].	200 m^2 each [19].
(2) 3D printed five-story apartment in Jiangsu Province, China/2014/Winsun Company [19].	Components of 3DP are pre-printed and assembled on-site (details of 3DP) CC (method) [81].	Cement, glass fiber, construction waste and hardening agent [81].	1100 m^2 This house withstands earthquakes [19].
(3) Earthquake-proof modular homes at Xian, China in 15 days/2015/ZhuoDa Group [89].	Ready-made modules of 3DP are pre-printed and assembled on-site in around three days. The LEGO brick technique is used (details of 3DP) [84].	The material mix is not published.	500 m^2 two-story villa in Xian. Theoretically resists a level-nine earthquake on the Richter scale [89].
(4) The world's first 3D printed two-story villa in 45 days/2016/HuaShang Tengda [89].	The building was printed on-site and required frame and print concrete by custom-built 3DP system (details of 3DP). Custom-built 3DP system (method) [86].	C30-grade concrete including rough aggregates. The volume of the concrete was 20 tons [89].	400 m^2 The thickness of the wall is 250 mm. This house should resist a level of eight on the Richter scale [89].
(5) 3D printed Chinese Classical Gardens of Suzhou at Shanghai, China/2016 [89].	Gigantic 3D printer 150 m × 10 m × 6 m was used (details of 3DP) [87].	Special concrete ink [87].	80 m^2 and 130 m^2 (both of them are garden-style courtyards in Shanghai, China) [89].
(6) 3D printed office in Dubai, United Arab Emirates/2016/Winsun Company [89].	The components of 3DP are pre-printed and take around 2 days to assemble on site with a size of 36 m × 12 m × 6 m [88].	A new kind of construction material [88].	240 m^2 Winsun Company pre-printed components [89].

Table 8 illustrates that although CC can achieve on-site 3DP, Winsun still pre-printed the structural components in factories instead of printing on-site. Even the earthquake-proof modular home at Xian was pre-printed and assembled on-site using the LEGO brick technique. However, HuaShang Tengda chose to print the world's first 3D printed villa on-site.

3.7. The Benefits for Construction Applications of 3DP, 3D Scanners and BIM Reported in the Dataset

Table 9 lists the benefits of 3DP at each construction phase.

Table 9. The advantages of 3DP in the different construction phases.

Phases	Benefits
Concept or pre-development phase [65]	The 3D model clearly shows the merits and deficiencies of the project.
Initial design phase [65]	Modeling and site layout planning.
Final design and submit phase [65]	Structural elements enhanced against earthquakes [59]; allows freeform architecture [59] and green design.
Project technical design and construction phase [65]	Efficient construction and enhances productivity in modular construction [64]; shortens the construction time.

The 3DP trend in China aims to combine with BIM to achieve automated construction, such as Urumqi International Highway–Railway combined Passenger Station and its North Square Entrance. The use of BIM can enhance site management and regulation and improve construction efficiency from all aspects.

Tao et al. [59] also demonstrate that 3DP could resolve the issue of weak connection points between components because it fabricates the node integrally. Moreover, 3DP can enhance earthquake resistance by increasing the connection size to avoid premature breakage under stress. Due to these beneficial characteristics, 3DP has engendered a revolution in the construction industry by creating "freeform construction." The San Francisco–Oakland Bay Bridge, which collapsed in an earthquake, was used as a case study to prove the importance of improving weak points. During the rebuild process, the sheer energy link design was added, and after the experience, the weakest part of the design was still the weld section but 3DP can reduce defects caused by the weld section.

In China, HUST developed SLS and SLM systems for printing large building components, but these systems are not able to generate components with a size larger than 1000 mm. The object's size is limited due to the technology of EOS GmbH-Electro Optical Systems (EOS), which is a state-of-the-art powder laser fusion AM technology. The largest project created by the largest EOS direct metal laser sintering (DMLS) system up to 2014 is $400 \times 400 \times 400$ mm^3. Therefore, it is necessary to separate the large component and then re-integrate it. However, this process is time and money consuming and incurs accuracy issues [20].

Wen et al. [20] introduced a multi-layer flexible preheating system, according to the self-adaptive fuzzy control technique, to address the non-uniform temperature field created by a single large preheating system. Moreover, they introduced self-adaptive preheating technology to prevent component distortion. They presented a multi-laser beam scanning method to enhance the precision and efficiency of a sports focus. They developed HRPS™ largescale laser sintering systems, which can create objects with dimensions up to $1400 \times 700 \times 500$ mm^3 and $1400 \times 1400 \times 500$ mm^3. This approach accepts numerous powdered ingredients, such as metal, composite powder, polymers, resin-coated sands and ceramic powders. They also developed a material with superior mechanical properties, which is known as high impact polystyrene (HIPS), a polymer blend of polystyrene (PS) toughened with polybutadiene rubber. The other suitable material for SLS is the mixture of polyamide (PA) and reinforcement particles. However, the size of the particles is too small for a significant density difference. Mixing these two materials is a challenge and performance is therefore limited. Wen et al. [20] developed the dissolution–precipitation process to make PA base materials, such as the PA/carbon fiber introduced by Yan et al. in 2011, PA/aluminum introduced by Yan et al. in 2009, PA/nanosilica introduced by Yan et al. in 2009 and PA/potassium titanium whisker introduced by Yang et al. in 2010. The carbon fiber under the scanning electron microscope (SEM) micrograph has a good effect on mechanical properties due to the particles dispersing and the PA aluminum has an excellent interfacial bond. The SLM system enlarges the project dimension to 500 × 500 × 400 mm^3 by the double-laser scanning system [20].

The combination of 3D scanning and 3DP is useful for heritage maintenance [56]. Xu et al. [55] developed a methodology to combine 3D scanning and cement mortar-based 3DP. This methodology represents a novel approach for replicating a decorative heritage element as the labor cost is expensive. A layering algorithm for model slicing and an enhanced nozzle path scan line algorithm were developed for the cement mortar placement process. The cup-shaped individual plinth was damaged and replicated through 3D scanning, then remodeled and reconstructed. This approach has a few limitations, viz: the requirement for improvement of the materials used; the high requirements for intricate carving patterns on the components using improved control of mechanical motion and a precise and flexible nozzle; and the restoration modeling algorithms for alternative or missing elements. Hence, enhanced printing and its compatibility are essential [55].

Leach [57] discusses the size issue of the architecture design and illustrates that 3DP models do not have the same properties as the full-size building, as the structural performance is affected. A large scale 3DP cladding of the Arachne facade project was designed by Chinese architect Lei Yu, Foshan, China, 2017, as an example. Therefore, 3DP was more suitable for the small scale and customized structure until 2017.

Kan and Lin [58] discuss the significant impact of 3DP on manufacturing a new type of TiAl alloy by selecting EMB. The SLM and EMB can be used to manufacture the metal material. However, the limitations are the material preparation for the TiAl alloy. The limitation is the microstructure evolution process of EBM samples during heat treatment.

With regard to the high-cost 3DP material, Fu and Liu [90] developed an innovative approach to enhancing the printed skin-truss structure by a mesh simplification strategy and maintained the similarity of the original. This kind of structure is used extensively in architecture, bridge engineering and aerospace.

Jia et al. [91] discuss how geopolymer and geopolymer-based composites could be applied in 3DP due to the low-temperature molding, cheaper cost and eco-friendly properties. For instance, 3DP can accept the aluminum–silicon acid polymer system.

Liu and Gao [64] demonstrate that 3DP is a significant symbol of the third industrial revolution and can be applied on the PC assembled inclined support node steel frame structure residential system. The self-supporting printed floor slab has a space truss support system in the middle of the slab, which can reduce the slab's weight. Thus, 3DP is an efficient method for volumetric modular construction using concrete structural units. 3DP can print a structure at once; therefore, the stability and the strength of the flexibility are higher than the traditional method.

Liu et al. [92] demonstrate the application process of converting a BIM model into 3DP STL format, importing the STL format into Cura 3D software, and adjusting the printing parameter set to produce the G-code used for the 3D printer.

Guo et al. [60] demonstrate the combination of BIM and 3DP in architectural decoration for a concealed fire-hydrant box stone door for a theatre project. The project department uses a method called "secondary conversion" to solve the opening angle and force degree, amongst other issues.

Lu et al. [62] discuss the combination of BIM and 3DP using Urumqi International Highway–Railway Combined Passenger Station and its North Square Entrance as a case study. This project includes many sophisticated techniques, such as 3DP, 3D laser scanning and an electronic distance measuring device (an intelligent photoelectric measuring instrument). In this project, RealWorks, Catia, Naviswork, Enovia (for data sharing and transfer platform) and Rhino were used for modeling curtain wall optimization.

Due to the unique style of the roof façade system and the consideration of the strength and life cycle, this project used 3DP, SRC (a kind of special glass fiber reinforcement cement) as the roof façade. The model data were imported into a 3DP system and then printed with SRC. The combination of

BIM and 3DP can enhance quality and efficiency. This project used BIM with 3DP through the design, production, constitution and management phases to maximize the architecture design in a high-quality and eco-friendly way. Figure 10 shows a few different architectural models' designs, considering different angles and curves for further examination.

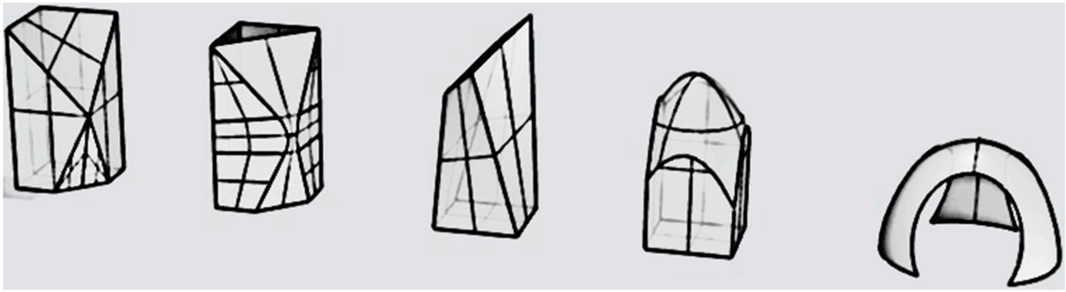


Figure 10. Five different designs of architectural models, including angles and curves for evaluating the performance of any proposed 3DP.

The BIM progress used on the Tecent Beijing Headquarters sought to use crush detection to optimize reinforcement arrangement and print a solid mold by 3DP to try to enhance the process of reinforcement implementation [93]. China Vanke cooperated with the National Aeronautics and Space Administration (NASA) on robotic-controlled processes for 3D houses [77].

Zhang and An. [82] state that the 3DP building is cheaper than conventional structures. Thus, it is suitable for low-income people and emergency housing. It is customizable and suitable for freeform construction, which is good for a natural disaster area. Furthermore, 3DP may be applied to services integration or decoration in buildings.

3.8. The Shape and Size of the Nozzle

The nozzle is a quintessentially important component in 3DP because it impacts upon the material's compressive strength and interlayer bonding [94,95]. The nozzle type can be divided into two categories, screw type and plunger-type [96], and common nozzle graphics are circular, elliptical and rectangular [97–99]. Table 10 provides detail on the common shapes, sizes and types of nozzle based on current shortcomings, advantages and improvement direction.

Table 10. Summary of the shape and size of the nozzle.

Topic		Limitation and/or Positive Impact	Optimization Direction/Aspects to Consider
Shape	Circular	Low percentage of contact area; low interlayer bonding; low compactness; specimens were easier to break; more freedom and ease to change the nozzle angle [97–99].	1. Nozzle shape design should consider the shape of specimens and the flowing speed of material [99]. 2. Nozzle shape design should consider the nozzle travel speed and the toolpath curvature radius [48]. 3. The size and shape of the side blades need to be further studied [100].
	Elliptical	Lower surface finish than that printed by rectangular nozzle [101].	
	Rectangular	Better compactness and compressive strength [97,101].	
	Nozzle with side blades	Better surface finishes than specimens printed by nozzle without side blades [102].	
Size	Diameter	A larger nozzle diameter produces better product density and tensile strength, while a smaller diameter leads to poor interlayer bonding but high dimensional accuracy. An increase in diameter leads to a decrease in the material transition distance, while a small diameter can lead to the rheology of material changes [48,103,104].	Nozzle size design should consider flowability of material, shape and size of specimens, dimensional precision requirements and the printing path of the material [104–106].
	Nozzle aspect ratio	Decreasing nozzle aspect ratio is beneficial to decreasing uneven mass distribution at corners [94].	
Special type	A multi-material nozzle	The mutual penetration of different materials, no calibration when depositing material [104,107].	To eliminate material contamination and waste, to improve calibration accuracy, and to avoid multiple nozzle collision [104,107,108].
	Multiple nozzles	Increase in printing time due to replacement of printing material; high precision calibration is required, which will lead to shrinkage of the material; printing filament discontinuity leads to a reduction in the integrity of the printing structure; lack of precision of nozzle due to parallax error [108–110].	

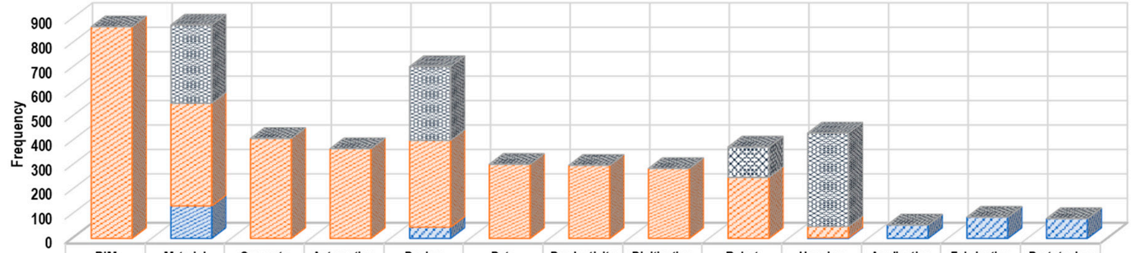
Material blockage presents a common and frequently occurring problem facing the nozzle [111]. In addition to its shape, the nozzle's size plays a decisive role. The nozzle material's properties (such as wear resistance, sealing and impact resistance) are also a key factor that cannot be ignored in minimizing this problem [97,101]. Hou et al. [96] and Shakor et al. [11] note that replacing aluminum bronze with beryllium bronze (which can better withstand the pressure of printing) as the material to produce a nozzle can effectively avoid material blockage [96]. However, an overweight nozzle material will reduce the nozzle's freedom and flexibility. In addition, with the development of printing materials, composite materials have increasingly replaced the traditional single thermoplastic materials, such as polylactic acid-filled stainless steel and iron. These composite materials will lead to the wear and deformation of nozzles and accelerate the use period [112]. Nozzle design is, therefore, at the core of 3DP technology. Further empirical research should be undertaken to test the optimum shape, size and material of nozzle design to improve printing quality.

4. Discussion

This paper presents a combination of a scientometric and content review of the concrete 3DP literature, including large-sized case studies and the available information about them. Major limitations presented in the selected literature show that the ink materials cannot achieve the optimized machinery properties, such as the strength both for off-site or on-site 3DP. The main challenges of 3DP are due to its implementation as on-site technology, and it can be less challenging where it is used as an off-site technology producing small-sized items. While the use of off-site technologies and modular construction are discussed and promoted by recent publications [31], the utilization of advanced technologies for on-site construction remains most challenging due to difficult site conditions affecting the performance of the 3DP [3,60,66,113].

In addition to the production challenges of 3DP, other issues include the quality of the components' surface finishes; the size of the components; the issue of the joint connection between off-site printed units; and the durability of the 3DP components in the natural environment due to the specific material properties requirement, such as zero slump. Previous 3DP practices using BIM show an efficient information exchange and model modification. However, the integration of BIM with 3DP has been reported as challenging and issues such as copyright and modeling responsibilities remain largely unexplored. A comparison of a few selected papers published in the first three years of the decade (2011–2013) with those from the last three years (2018–2020) shows that the main concerns have shifted from prototyping and applications to BIM and concrete materials. However, Yu et al. [77] report that 3D modeling design software is not yet mature enough for 3DP purposes. In addition, new information technologies, and software and hardware interoperability with 3DP systems are growing concerns mentioned in the literature. Su et al. [66] and Guo et al. [60] mention other limitations which include the software, hardware facility and standards specification, the size of the 3D printer and the accuracy of the printed elements. Aoki et al. [114] introduce a new augmented reality (AR) 3D modeling system with an air spray-like interface and a novel data structure, which is octet voxel, to represent the design model. This approach has been testified based on the user test, and users can design individual components in a short period with a simple interface.

Figure 11 shows the frequency of keywords within a different set of documents collected from scholarly papers and the website content provided by different relevant companies. Interestingly, the content analysis of 50 websites of commercial companies shows that robots and housing applications are of the most concern in practice. Zhang and Su [65] report that standard concrete cannot be adopted, the processing of the additive materials and the size of the 3D printer are limitations, the size of material aggregates is significant and the admixture mechanism properties may change when added into the 3DP "ink". Therefore, the transformation between the software and reality is vital. The major limitation mentioned is that the windows, doors and pipework cannot be printed at the same time. Figure 12 presents a set of the most frequent words within the datasets and gives an overall idea about the main concerns within the literature or within the industry. The figure shows the shift from technology, manufacturing practice and process definitions at the beginning of the decade to the integration of 3DP with BIM, automation and productivity at the end of the selected decade from 2018 to 2020. The figure also shows that conversation in commercial companies is revolving around housing applications as a high demand market and the introduction of using concrete by 3DP.



	BIM	Material	Concrete	Automation	Design	Data	Productivity	Digitization	Robot	Housing	Application	Fabrication	Prototyping
Websites	0	320	0	0	302	0	0	0	124	382	0	0	0
2018-2020	866	420	409	367	355	303	299	286	250	47	0	0	0
2011-2013	0	133	0	0	46	0	0	0	0	2	55	87	81

Figure 11. Comparison of the frequency of keywords within the selected documents, which include scholarly articles and selected commercial companies' websites.

2011–2013 2018–2020 2019 (commercial companies)

Figure 12. Dominated concepts and main concerns within the literature or the industry.

This paper has discussed some of the practical limitations reported in the literature. For example, Tao et al. [59] highlight that the 3DP envelope height limits the size of 3DP products and the accessibility of multiple-level structures. A challenge that should be addressed is the low corrosion resistance of the materials used in 3DP for reinforcement, which affects the durability of the components. Zhang and An [82] further mention quality control of the surface and assurance of the printing components, such as the earthquake resistance. In addition, Yu [61] demonstrates two other limitations, architecture design (given material limitations) and 3DP machinery, which require high accuracy and automation. Furthermore, Hager et al. [81] state that the potential consequence for widespread adoption of 3DP is increasing unemployment. Li [63] discusses the development of a new self-climbing 3D printer to solve the problem regarding the difference between the 3D printer and the building height. This machine can be installed on the building and climb along with the structure. Further development is the introduction of the multi-head printer to overcome the low outcome caused by the single printer head. Li [63] also demonstrates the future advancement of 3DP in the architecture, construction, engineering and operations (AECO) industries via a material with high inherent safety and excellent printability. Li [63] also investigates the development of a multi-print head, distributed, self-climbing 3D printer to enhance printer efficiency and safety levels. One of the practical implications of 3DP development is that automated versions do not succumb to the labor shortages that grip China's construction industry, a situation that is further exacerbated by the global COVID-19 pandemic [65].

Table 11 lists the benefits and limitations mentioned in the sample literature. The embryonic adoption of 3DP in China is largely focused on experimentation and theoretical synchronization, even before the theory. For instance, the "ink" that Winsun used contained construction waste and industry debris combined with high-grade quick-dry cement and glass fiber to achieve the desired strength [1]. However, the process details are still unfolding. The literature shows that construction waste could be reused within the 3DP "ink", and Winsun company real practices followed in some articles.

Table 11. A summary of the benefits and limitations experienced in previous practice within 3DP literature.

Factor	Current Practice and Limitations	Future Directions and Needs
Material [77]	The materials used for 3DP are challenging in meeting the optimized standards, such as shrinkage, extrudability, flowability, setting time, buildability, interlayer bonding, mechanical properties and layer-by-layer appearance. Some requirements can also conflict, such as buildability and flowability. However, one of the significant advantages of 3DP is to save materials and cost. The material difficulty meets construction standards. Thermal insulation and energy-saving, earthquake resistance and economy [77].	Efficient construction methods regarding cost, materials, time, safety and management; potential for customization and freeform construction; reduction of waste during the construction phase; eco-friendly practice; diversity of materials practice; resource consumption; quality control/assurance for the surface finish.
Size [77]	In 3DP literature, all components are printed off-site, except for those generated by HuaShang Tengda. There is no detailed information about the off-site printed component dimensions but the highest 3DP residential building is a five-story apartment in Jiangsu Province, China.	Products (quality, size, duration, building height); control budget (high accuracy).
Laboratory or on-site practice; modular construction	High production costs and conventional printing materials are still the challenges of 3DP in modular construction [115]. Lack of investigation for post-occupancy satisfaction, and environmental measures.	Present an application for hollow concrete structural units (volumetric modular), such as the entire bathroom or kitchen, which can enhance the flexibility of the house space [64].
Durability	Low corrosion resistance for reinforcement but high earthquake resistance [59].	Durability indicators need to be measured in different contexts and climates.
Software interoperability	Except for the significant software Revit and Navisworks, Rhino and Catia are used for curtain wall and cooperated with Revit. RealWorks is a tool for point cloud data processing. Enovia is a data sharing and transfer platform to provide a ground for a project.	Little information included in the sample articles regarding software compatibility issues.
Productivity and cost effectiveness	High dimensional accuracy and the complex shapes of parts leads to a dramatic increase in production time, which limits productivity [116]. To meet the production standards, the decrease in build time leads to an increase in process time. Expensive post-processing is one of the main expenditures [117–119].	Relieves labor intensity on the construction site and also in the office. The market evolution, supply chain management, production, and machinery costs and the reduction of reoccurring costs. Multiple nozzles, to optimize and reduce printing steps.
Legal	Lack of standards, guidelines, evaluation criteria, blockchain instructions and standards for 3DP practices.	Copyright/standard applicable for 3DP; unemployment.
Heritage applications [55,56]	Leung et al. [56] demonstrate how to use 3DP to repair historical buildings like the lighthouse at Penghu, between Xiamen and Taiwan. It uses state-of-the-art Revit to rebuild 3D virtual construction, save input detail into 3DP and then apply 3DP.	Earthquake resistance after construction.
Stakeholders and workers	An overall shortage of appropriately trained workers in AM, and limited opportunities for collaboration and exploitation of ideas [119].	Knowledge reserve and skill cultivation.
Integration with BIM	A significant lack of experimental data and validated models for 3DP parts, lack of compatible conversion files [120].	Open BIM has the potential to integrate more information and improve workflows for 3DP.
Metrology	Fundamentals of optical interrogation of the surface, such as the compromise between spatial resolution and field of view [121].	High spatial resolution, fast and compatible with the production environment.

Table 11. *Cont.*

Factor	Current Practice and Limitations	Future Directions and Needs
Binder	Organic binders work well among different binders, however they can affect the plastic parts of 3DP machines during long-term operation, and the residue from binders is difficult to remove during sintering [71].	Sustainability of material and the continuous effect of binder on the mechanical properties of the material.
Calibration	Lack of simulation and calibration models based on a structured framework. The big diversity of shape and size of 3DP products [122].	Integration of physical knowledge into models based on principles of model calibration.
Pump	Delivery segregation of particles; material blockage during high-pressure pumping process; discontinuous material based on slow pumping process [99].	Insurance of the fluidity and constructability of material.
Geometrical imperfection	Prone to produce a layer-by-layer appearance [123]; layer deposition based on gravity, the thickness of the layer and material property [23].	Development of material to improve the buildability. The improvement of machines, such as adding side flank with a nozzle.
Monitor	Difficulty in acquiring fast and accurate measurements of the temperature, cooling rate and residual stress [124].	Implementation of other optical technology with higher precision, camera and ultrasonic C-scan, and in-process correction to compensate for the defect.
Industrial promotion	Lack of incentives for 3DP-transformation in industries; supply chain complexities; lack of skills and knowledge; regulation and liability issues [125].	Government support and construction market stimulus.

Moreover, most Chinese articles focus on technology applications in different contexts and are interested in the practical implications of 3DP. Therefore, this means the selected Chinese papers rarely offer a radical innovation in this field; rather, they rely on world-wide developments in the 3DP area. For instance, HUST, China, further developed the system for large objects to solve the restrictions on not being able to print buildings larger than 1000 mm on SLS and SLM systems [3]. However, the current literature shows that many other countries, such as Malaysia, have not accepted the latest prototypes of 3DP in practice [126]. A future direction would be to investigate barriers to utilizing 3DP technology in different construction contexts and projects. Evaluating industry readiness, particularly for small and medium-sized construction companies, is critical for a successful diffusion process.

Figure 13 presents a taxonomy of 3DP systems, digital tools, operation methods and required materials for 3DP. While many studies have mentioned that the shape and size of nozzles could influence the quality of printed components, few studies have conducted experiments to demonstrate how the design of the nozzle could be optimized. However, a series of experiments needs to be conducted to explore any potential relationships between the nozzle and the mechanical performance of printed components. Another question that should be addressed is how the quality could be improved accordingly. Future studies should consider the design and implementation of various sizes and shapes of the nozzle. At the technical level, Rhino software is helpful in designing the shape and size of the nozzle to then be used by the 3D printer. The impact of different factors should be taken into account, such as the properties of the material, the printing environment and the amount of printing in order to reduce accidental error. In addition, with the rapid development of 3DP technology, material technology and manufacturing modes, large-scale production and high-precision customization production will become the mainstream of the future market. Thus, the main challenges to future nozzle design are to optimize the nozzle design to achieve high dimensional accuracy and printing quality; strengthen the connection between nozzles from different production steps and the connection between nozzle and other intelligent equipment to increase production efficiency; and find the balance between high precision production and minimum printing period.

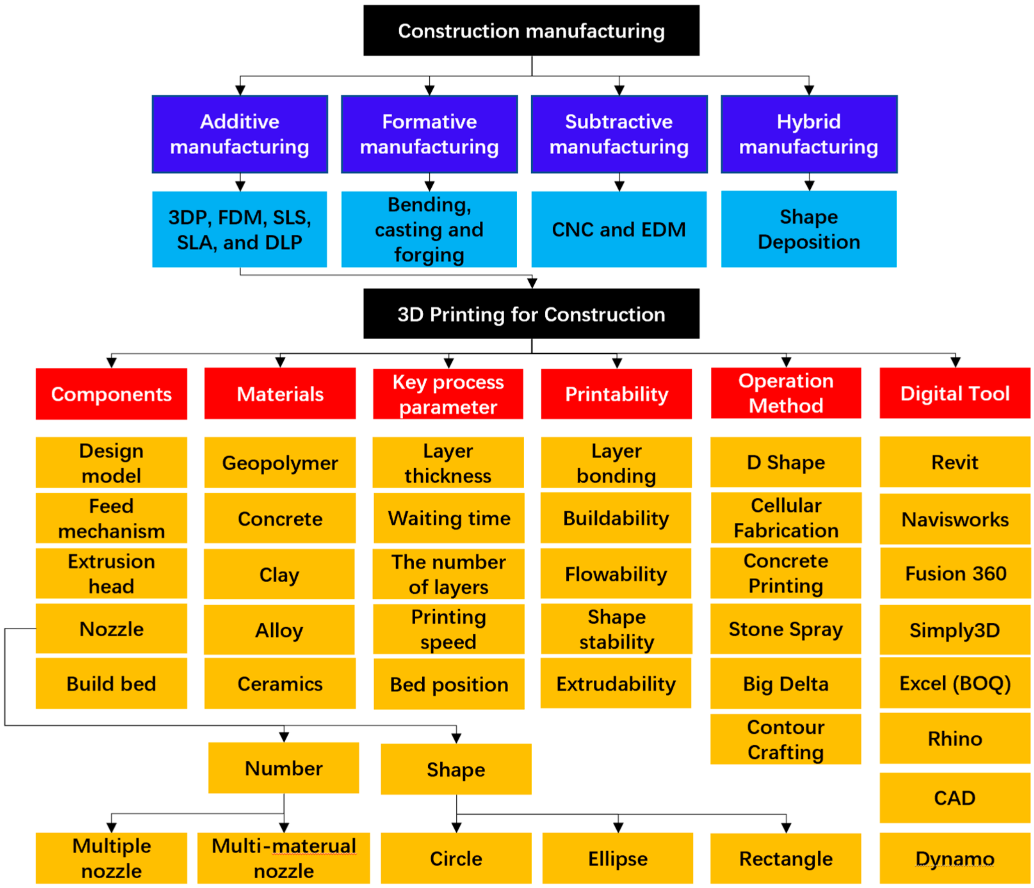


Figure 13. Taxonomy of 3DP systems, digital tools, operation methods and required materials for three-dimensional printing in construction. Note: FDM: fused deposition modelling; SLS: selective laser sintering; SLA: stereolithography apparatus; DLP: digital light processing; CNC: computerized numerical control; EDM: electrical discharge machining; BOQ: bill of quantities.

5. Conclusions

This paper presented lessons that have been learned in the previous decade from the selected contexts and a few practices conducted in China using a systematic review of the literature, particularly those articles focusing on the nozzle, which is a key component of 3DP. A systematic review was conducted to identify relevant articles and the content of the relevant articles was critically reviewed to identify the limitations of the current methods. In addition, 50 websites of commercial companies were chosen for further content analysis and identification of the main concerns and keywords used by practitioners. 3DP limitations in real practice (such as size, productivity measures and interoperability with other software tools) require a considerable amount of work in order for them to be widely adopted by a variety of small to large companies. Another concern regarding the widespread implementation of 3DP is to maintain a high level of safety where there is interaction between humans and machines. Adequate availability of required materials for the 3DP performance with the correct attributes (easily pumpable, short setting time and good interlayer performance after curing) is another concern reported in the literature. Other challenges at the operational level include physical progress based on the cooperative path plan of a multi-printhead printer using artificial intelligence, such as the optimized mathematical model and post-occupancy satisfaction measures and benchmarks.

The benefits, limitations and further development directions of 3DP are similar between China and other countries according to both the English and Chinese articles reviewed in this paper. Therefore, it would be mutually beneficial for China and other countries to cooperate with each other. This article also discussed the limitations, challenges, and optimization directions of the nozzle in 3DP, based on size and shape. The potential relationship between the nozzle and the mechanical performance of printed components still requires further study. A taxonomy was presented of 3DP systems and associated tools based on the systematic review conducted, which provides a big picture of the different directions and focuses on the literature. This will be helpful to future scholars and practitioners in understanding and organizing the diverse range of methods and tools and for conducting comparison-based evaluations and investigations.

3DP resides at an embryonic stage of development and there is wide scope to develop this field in the decade ahead to facilitate the concept of Industry 4.0. The utilization of 3DP can be controversial as an advanced on-site technology versus the application of off-site technologies promoted by different literature. This review can be helpful to scholars to learn from the current practices because it provides an overview of the main challenges of a 3DP implementation process.

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Abbreviations

3D	Three-dimensional
3DP	Three-dimensional printing
BIM	Building information modeling
FDM	Fused deposition modeling
CC	Contour crafting
AM	Additive manufacturing
SLS	Selective laser sintering
SLM	Selective laser melting
EBM	Electron beam melting
MJ	Material jetting
BJ	Binder jetting
SLA	Stereo lithography appearance
DED	Directed energy deposition
C-Fab	Cellular fabrication technology
VMA	Viscosity modifying agent
FRP	Fiberglass reinforced plastics
GDP	Gross domestic product
HUST	Huazhong University of Science and Technology
DMLS	Direct metal laser sintering
HIPS	Polystyrene
PA	Polyamide
SEM	Scanning electron microscope
AECO	Architecture, engineering, construction and operations
PS	Polymer blend of polystyrene
NASA	National Aeronautics and Space Administration
EOS	Electro-optical systems

Appendix A. Keywords and Eligibility

Tables A1 and A2 and Table 11 show the keywords and the eligibility criteria set out during the research process, which were the resources used for the analysis.

Table A1. Keywords and eligibility—Scopus.

Combinations of Keywords	Limitations (Scopus Copy Not Finishes)	No of Result Paper	Total
3dp or '3D print*' + construction or build* or architectur* + chin* or 'hong kong' or taiwan or macao + All (BIM or 'Building information model*')*	Exclude Conference Paper, Conference Review. Exlude Conference Proceedings and Book Series.	1 (English) 1 (Chinese)	20
3dp or '3D print*' + construction or build* or architectur* + chin* or 'hong kong' or taiwan or macao + All ('3D scan*' or laser or scan*)*	Exclude 2019. Exclude Physics and Astronomy, Medicine, Agricultural and Biological Sciences, Biochemistry, Genetics and Molecular Biology, Pharmacology, Toxicology and Pharmaceutics. Exclude Conference Paper. Exclude Conference Proceedings and Trade Publications.	5 (English) 7 (Chinese)	Laser (E): 3 repeated with Robot (E). 1 repeated with BIM and Robot (E).
3dp or '3D print*' + construction or build* or architectur* + chin* or 'hong kong' or taiwan or macao + All (robot* or automat*)*	Exclude 2019. Exclude Agricultural and Biological Sciences, Biochemistry, Genetics and Molecular Biology, Physics and Astronomy. Exclude Conference Paper, Editorial. Exclude Conference Proceedings.	4 (English) 2 (Chinese)	Robot (E): 3 repeated with Laser (E). 1 repeated with BIM and Laser (E). 1 repeated with BIM.
3dp or '3D print*' + construction or build* or architectur* + nozzle +shape or size*	Exclude Medicine, Physical and Astronomy, Biochemistry, Genetics and Molecular Biology, Agricultural and Biological Science, Pharmacology Toxicology and Pharmaceutics, Immunology and Microbiology. Exclude 2019. Exclude Conference Paper, Conference Review, Editorial. Exclude Russian. Exclude Conference Proceedings, Trade Publications, Book Series.	34 (English)	34

Table A2. Keywords and eligibility—CNKI.

Combinations of Keywords	Limitations	No of Result Paper	Total
ABSTRACT (3d printing and engineering) + ABSTRACT (architectur) + ALL (BIM)	Include Mathematics, Mechanics, Physics, Resources Science; Architecture/Energy/traffic/electromechanics, etc; Macro-economic Management and Sustainable Development; Theory of Industrial Economy; Economy of Traffic and Transportation; Culture Economy; Information and Post Economy; Market Research and Information and Management Science.	3 (English) 15 (Chinese)	62
ABSTRACT (3d printing and engineering) + ABSTRACT (architecture) + ALL (3D scan OR laser OR scan)	Include Mathematics, Mechanics, Physics, Resources Science; Architecture/Energy/traffic/electromechanics, etc; Macro-economic Management and Sustainable Development; Theory of Industrial Economy; Economy of Traffic and Transportation; Culture Economy; Information and Post Economy; Market Research and Information and Management Science.	5 (English) 25 (Chinese)	Laser: 1 repeated with BIM
ABSTRACT (3d printing and engineering) + ABSTRACT (architecture) + ALL (robot OR automat)	Include Mathematics, Mechanics, Physics, Resources Science; Architecture/Energy/traffic/electromechanics, etc; Macro-economic Management and Sustainable Development; Theory of Industrial Economy; Economy of Traffic and Transportation; Culture Economy; Information and Post Economy; Market Research and Information and Management Science.	2 (English) 12 (Chinese)	Robot: 4 repeated with BIM

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