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REVIEW ARTICLE

Exploring the role of 3D concrete printing in AEC: Construction, design, and performance

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Abstract

The use of concrete, which has an essential place in the construction sector, is becoming increasingly widespread in the sector with the additive manufacturing method. On the other hand, three-dimensional concrete printing (3DCP) technology, the centre of attention of many researchers, is still a developing method in the sector. Analyses on the current status of 3DCP are considered important in guiding academic studies on the potential and future of the subject. In this context, the study aims to evaluate the current status and potential of 3DCP technology in the AEC (architecture, engineering and construction) industry. In this study, the bibliometric analysis method was used to identify, select, evaluate and systematise the research literature on three-dimensional concrete printing technology in building production for the purpose of the study and to create new perspectives for future studies. According to the criteria determined within the scope of the study, 241 articles were reached in the Web of Science database. VOSviewer and biblioshiny programmes were used to determine data such as annual number of publications, publication production of countries, number of citations, and keywords. According to the findings based on the content of the reviewed articles, research on 3DCP technology is mainly focused on the fields of construction, performance and design. In this context, 35% of the 60 most cited papers were focused on construction, 57% on performance and 8% on design. According to the study's output, further research and application are needed in the field of 'design'. In this study, it is seen that 3DCP technology is still an emerging field and there is a need for further research and application in terms of 'design' in terms of the AEC sector. In this context, it is thought that the study will provide important references in terms of processes and trends in the sector.

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1. Introduction

One of the new technologies brought by Industry 4.0 is the additive manufacturing method that enables the three-dimensional (3D) output of the product designed in virtual/digital environments. Additive manufacturing is defined as a method of creating objects by adding layer upon layer using 3D model data [1]. This production method has been developing since the invention of the first 3D printer, one of the additive manufacturing technologies, in 1983, and today, it has become a rapidly growing, developing, and complex technology that produces complex products. While it was both expensive and had complex technical equipment in the first years of its invention, it has become an accessible technology that can be used even in daily life over time. Especially important industrial sectors such as automotive, aviation and aerospace have experienced radical process changes by adopting this digital technology to increase quality and efficiency.

In the additive manufacturing lens, the construction sector is a sector that offers opportunities for effective use, but where this technology is used relatively less because it produces large-scale products compared to other sectors. The most important component of the sector in this technology is three-dimensional printing (3DP) applications [2]. 3DP is a building technology used as an alternative to traditional moulding methods [3]. This technology creates building elements by assembling concrete layer by layer based on a computer model by means of a robot or similar device. This allows the production of non-linear and architecturally complex designs. Although it requires an extensive and challenging process, significant progress in the construction industry is being made with the development of printing systems and printing materials used today [4]. The advancement in automation and digitalisation in the construction industry through 3DP applications enables construction companies to increase efficiency, reduce project delays and cost overruns, manage complexity, and improve safety, resource efficiency and quality across their operations [5, 6]. It also provides advantages in a wide perspective, such as increased productivity and design creativity, creation of new markets/industries, creation of new business environments, greater sustainability and durability, shorter construction time, rapid prototyping, with a reduction in transportation costs, storage space required for materials, labour costs, worker injuries/deaths, material waste [7-11]. In addition to these advantages, 3DP applications have offered a different perspective on building production; it has been a tool for users to create prototypes of original and creative works and to transform their abstract thoughts into concrete [12]. Especially in the design-oriented "architectural discipline"; thanks to its ability to create complex objects with differentiating features, it has become an important technology for producing customised products.

As the use of 3DP becomes the key to modern product development, research into large-scale production is beginning to reveal potential applications in building production [13]. The use of concrete, which has an important place in the construction sector, in structures with additive manufacturing methods is becoming increasingly widespread in the sector [14]. In construction, this technology combines CAD or BIM software, robotic arms, extrusion systems and traditional and advanced materials [8]. There are many examples of applications of 3D printing technology in the construction sector in the world (Office of Dubai Municipality) [15], The BOD., KampC, Tecla, Project Milestone. In Fig. 1, there are 42 examples of buildings/applications with different locations and qualities produced with 3D printing technology. When the buildings analysed in order to investigate the relationship between architectural planning/design and production for 3D printing applications, which are expected to play an important role in building production processes in the future (Fig. 1);

- It has been observed that there has been an increase in the number of buildings applied with 3DB in recent years.
- Differences are observed in the mass formations of the buildings depending on the variability of the design and usage conditions.

Structures analysed: a) 5-storey building constructed with 3D printer technology, China, 2014; b) Buildings produced with 3D printer technology, China, 2014; c) Lewis Grand Hotel, Philippines , 2015; ç) Public recreation structure, China, 2016; d) 2-storey villa, China, 2016; e) Apis Cor house, Russia, 2016; f) Office structure, Dubai, 2016; g) The BOD, Kopenhag, 2017; ğ) An exhibition prototype, Italy, 2018; h) Minimalist house, USA, 2018; ı) Yhnova project, France, 2018; i) Geo House, Italy, 2018; j) Vivienda 3D, Spain, 2018; k) Lotus House, China, 2018; l) City hall, Dubai, 2019; m) House project, America, 2019; n) Village housing project, Mexico, 2020; o) KampC house project, Belgium, 2020; ö) Prvok, Czech Republic, 2020; p) Insulation houses, China, 2020; r) House project produced with 3D layered technology, USA, 2021; s) House project made of local materials, Italy, 2021; ş) Book reading cabin, China, 2021; t) School building, Malawi, 2021; u) House made of concrete (Milestone Project), Netherlands, 2021; ü) Housing structure, Germany, 2021; v) Residential building with office use, Turkey, 2021; x) Economic housing structure, Kenya, 2021; y) The House of Dust, Germany, 2021; z) Housing structure, India, 2021; 1) Residential structure, 2022, New Zealand (Paremoremo House) 2) Residential structure, USA, 2022 (House Zero) 3) Residential building, New Zealand, 2022 (Creators Forest Lake) 4) Residential building, New Zealand, 2022 (Huia House) 5) Residential building, South Africa, 2022 (UJ House) 6) Residential structure, USA, 2022 (Islandia Print) 7) Residential structure, USA, 2023 (Las Casitas) 8) Building element, 2023 (Living Seawalls) 9) Housing structure, USA, 2023 (3D Printed Houses in Florida) 10) Otel yapısı, ABD, 2023 (El Cosmico) 11) Hotel structure, USA, 2024 (The Genesis Collection at Wolf Ranch) 12) Apartment building, Germany, 2024 (PERI 3D Construction)

Fig. 1. Buildings produced with three-dimensional printing technology (source: authors)

- The roofs of the buildings have various applications (flat, porch, gable roof and dome roof etc.).
- In terms of function, it is observed that the majority of 3DP production is residential projects.
- Designing buildings with different combinations using 3DP requires interdisciplinary co-operation. The buildings examined are the result of a teamwork; various organisations such as companies, architectural offices and universities have carried out trials and applications with 3DP systems.
- When the materials of these buildings are analysed, it is seen that 39 out of 42 buildings were constructed with concrete. Concrete material is one of the most widely used materials in the construction sector.

This method, which is still developing in the construction sector, is the subject of many academic researches and there are important studies [16-29]. However, the basic scientific understanding of the relationships between design, material, process and product is still being explored [14].

2. Methodology

In this study, the bibliometric analysis method was used to identify, select, evaluate and systematise the research literature on three-dimensional concrete printing technology in building production for the purpose of the study and to create new perspectives for future studies. The selected articles were examined using quantitative bibliometric analysis, a statistical and applied mathematical analysis of bibliographic data that has been frequently used in recent years for the analysis, evaluation and prediction of the status of different research areas [30].

Data collection was performed using the Web of Science (WoS) Core Collection database. The scope of the literature was limited to peer-reviewed journal articles and reviews, and other types of publications, such as books or conference proceedings, were eliminated due to the significant volume of scientific work published each year. In the WoS database, 247 articles published in the field of architecture and engineering in the category of "Construction & Building Technology or architecture" were accessed using the keywords '3D print* and concrete and architectural design or architect* or structure* or building design or construct*'. The range of these publications covers studies between 2018-2024. This timeframe was chosen because 3DP technology is relatively new, widespread, and rapidly evolving. Finally, only publications written in English were included in this study. Table 1 summarises the main parameters used in the WoS database search and their corresponding information.

The analyses of the publications accessed from the Web of Science database were obtained through VOSviewer and Biblioshiny. It was observed that three-dimensional printing technology is used in many different fields, such as chemistry, the biomedical field, and the aircraft industry, and there are publications in the WoS database. For this reason, among the 247 publications that reached the first stage, those that were outside the scope of the study were examined in full text by considering abstract, content, and keywords, and articles that were unsuitable for further analysis were eliminated. In the last stage, 241 publications in the field of architecture and engineering that are relevant to the subject were reached. The outputs/analyses of these publications are included in the 'findings' section.

3. Findings

Detailed data analyses (number of publications and citations of countries, keyword analysis and content analysis of publications) are included in this section.

The amount of the annual number of publications published in a field and their distribution by years is important in terms of showing the development direction of the subject and the scope of knowledge. Fig. 2 shows the trend of the annual number of articles published in the last six years. Looking at the studies on three-dimensional concrete printing technology in the field of engineering and architecture in the last six years, from 2018 to the present, it is seen that there is a continuous increase. As of January 2024, there are currently four publications on the subject.

Table 1. Wos-based research criteria

Database	Research Criteria
Web of Science (WoS) Core Collection *Software:* RStudio-Biblioshiny, VOSviewer	*Keywords:* 3D print* and concrete and architectural design or architect* or structur* or building design or construct* *Web of Science Category:* Construction & Building Technology or architecture *Document Type:* Article and Review *Publication Language:* English *Publication year range:* 2018-2024 *Research Area:* Architecture, engineering

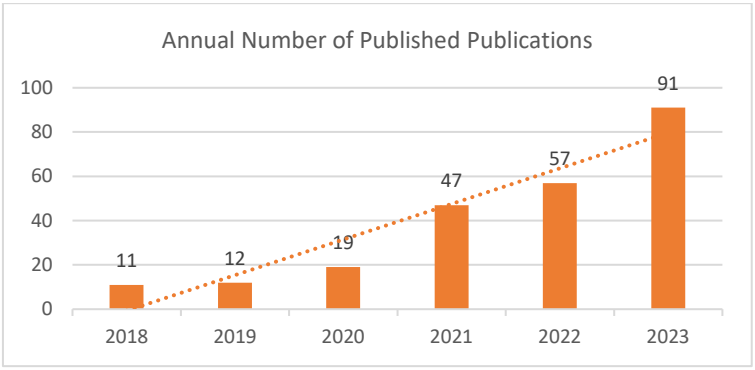
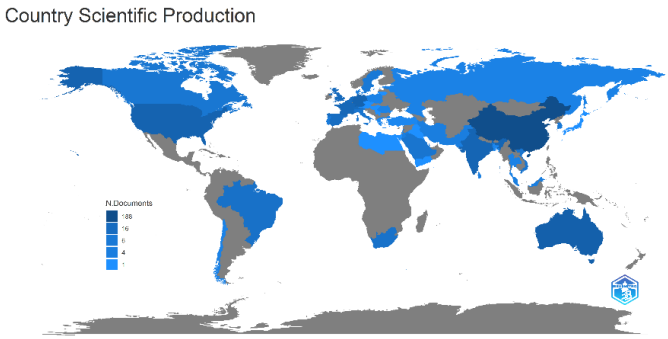


Fig. 2. Annual number of published publications

Until 2020, since three-dimensional concrete printing is still an emerging trend in the AEC sector, it is seen that research on 3DCP technology has gained significant momentum since this year. This situation shows significant developments in the field, which is reflected in publications with increasing applicability.

Fig. 3 shows the number of publications made by countries on the subject. When we look at the first five countries, we see China, Australia, Germany, the USA, and France. The UK, Belgium, India, the Netherlands and Singapore follow these countries. In this context, China has the highest amount of research on this subject and is an important resource for the future of the subject. In addition, this situation in the number of publications also shows the importance that the country attaches to the subject.

In Fig. 4, the top 10 countries with the highest number of citations among 241 publications are listed. Accordingly, China ranks first with 1136, followed by Australia, Belgium, England, Germany, the Netherlands, India, South Africa, Italy and Singapore.



Country	Number
China	188
Australia	41
Germany	34
America	33
India	28
France	23
Singapore	20
United Kingdom	19
Netherlands	18
Switzerland	18

Fig. 3. Countries' scientific production (Biblioshiny)

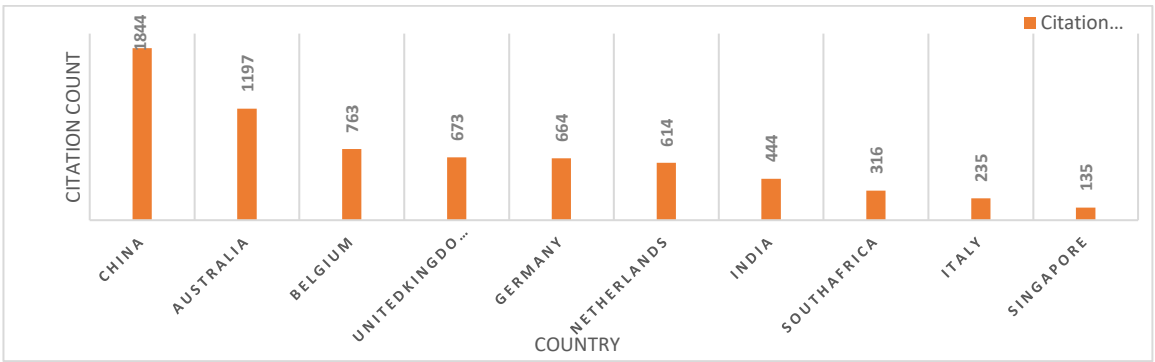


Fig. 4. Top 10 most cited countries (Biblioshiny)

Keyword occurrence analysis can identify keyword clustering, clarify the development direction of the field and summarise emerging research in an academic field. Fig. 5 shows a visualisation of keyword cluster occurrences in the selected literature through the VosViewer programme. Two counting methods for keyword analysis are available here: binary and exact counting. The binary method counts only the presence or absence of a term without taking into account repetition within an article. On the other hand, the total count requires recording the occurrence of each word. The total count method was chosen in this study as it offers a more comprehensive analysis of the actual outputs of the research topics [30]. The analysis according to this method (Fig. 5) shows five different clusters (green, red, blue, purple and yellow), each representing an area where 3DCP technology is used.

The representations of the five main clusters in the keywords can be expressed as follows. It can be seen that the red cluster has "mechanical properties, sustainability" links shaped around the concept of "3d printed concrete", the green cluster similarly has "additive manufacturing, reinforcement" links shaped around the concept of "3d concrete printing", the blue cluster has "concrete 3d printing, extrusion" links shaped around "rheology", the yellow cluster has "printability, 3d printing concrete" links shaped around "buildability" and the purple cluster has "concrete, thixotropy" links shaped around "3d printing". With this analysis, which summarises the research with keywords, the still developing structure, connections, trends and possible research topics of the subject can be seen conceptually. Accordingly, it can be seen that there are studies on the applicability of 3DCP in both engineering and architectural intersection, but the process continues due to the still developing structure of the subject."

Fig. 6 shows an analysis of the tripartite relationship of the publications selected within the scope of the study in terms of their authors, the keywords they use and the countries in which they were published. When the relationship between authors and their countries is analysed, China and Germany have the most studies with these keywords.

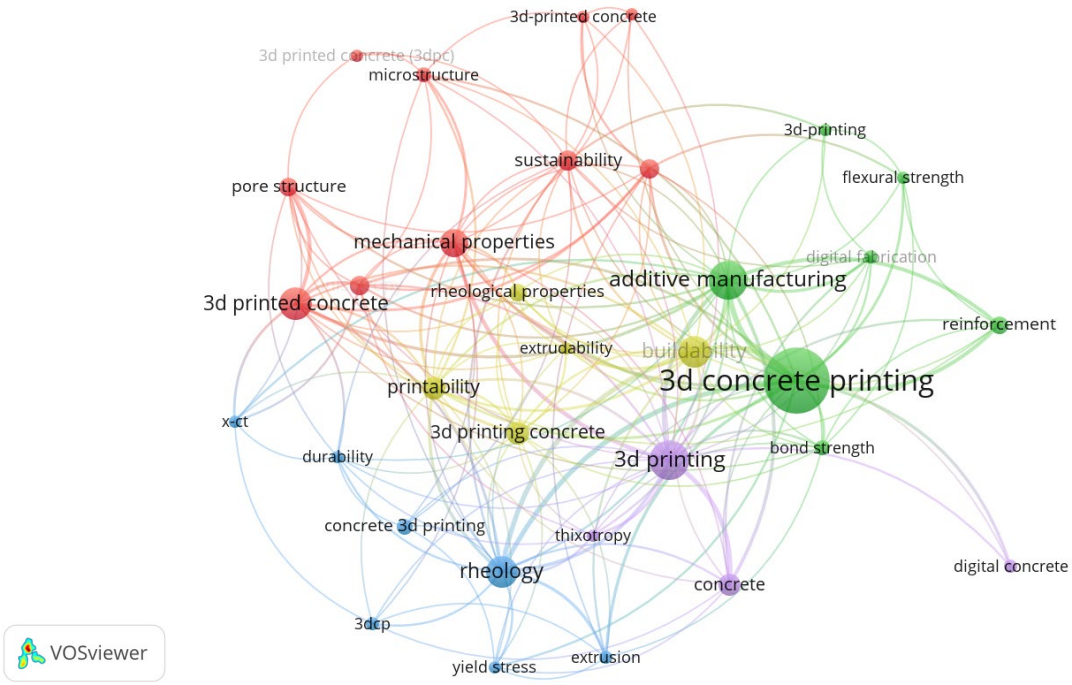


Fig. 5. Keyword cluster formations (co-occurrence analysis) (VOSviewer)

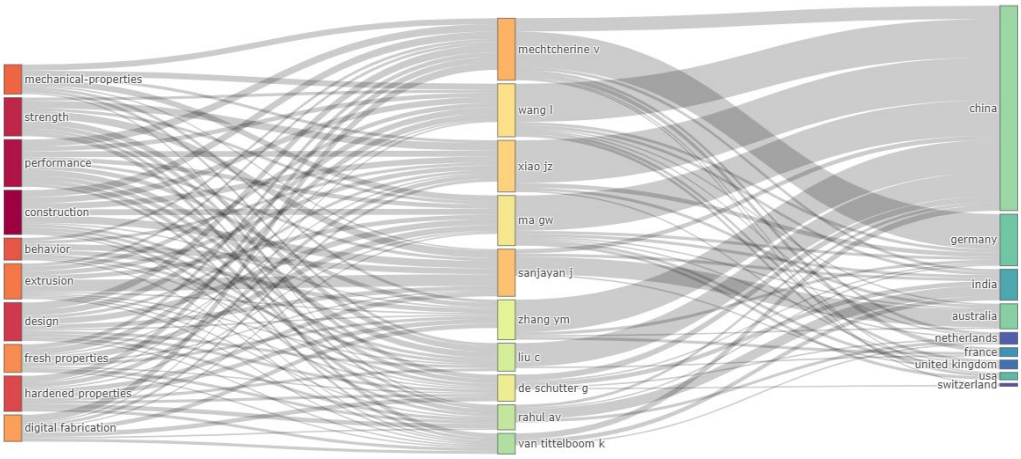


Fig. 6. 'keyword, author and country of publication' relationship network of publications (Biblioshiny)

India, Australia, Netherlands, France, the United Kingdom, the USA and Switzerland follow these countries. When the most trending keywords for the subject are analysed, it is seen that the words 'strength, construction and performance' come to the fore. The limited number of studies on the fresh/fresh properties and behaviour of the material, and therefore the limited number of keywords, shows that this subject still needs to be developed. This may indicate that future studies on these areas may be trending topics in the literature.

The analysis of the co-occurrence network made through Biblioshiny is shown in Fig. 7. Accordingly, it is seen that the research and development studies carried out as a result of the bibliometric analysis of 3DCP technology in building production are gathered in two main clusters (blue and red). At this point, in the analysis of the two clusters, it is seen that the most basic keywords are construction, performance and design. When the next sub-clusters are analysed, engineering-based keywords such as mechanical properties, fresh properties, digital fabrication, and cement-based materials emerge.

When we look at the Clustering by Coupling analysis, another keyword plus analysis supporting this situation, it is seen that this area is grouped into three groups (Fig. 8). These three groups are shown in different coloured legends (red, blue and green). When we look at the keywords belonging to the groups. Group 1 (blue) ranks first with the keywords construction, performance, and design. These groups are followed by red (hardened properties, strength, construction) and green (performance, strength, extrusion) clusters.

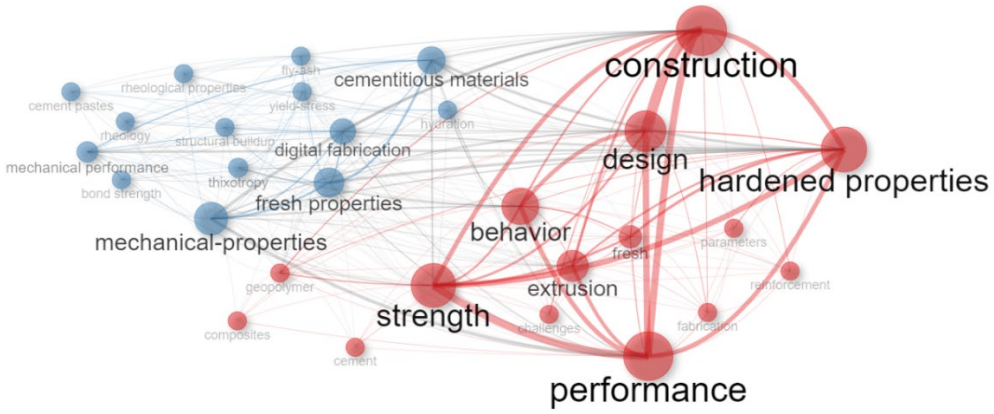


Fig. 7. Co-occurrence network (Biblioshiny)

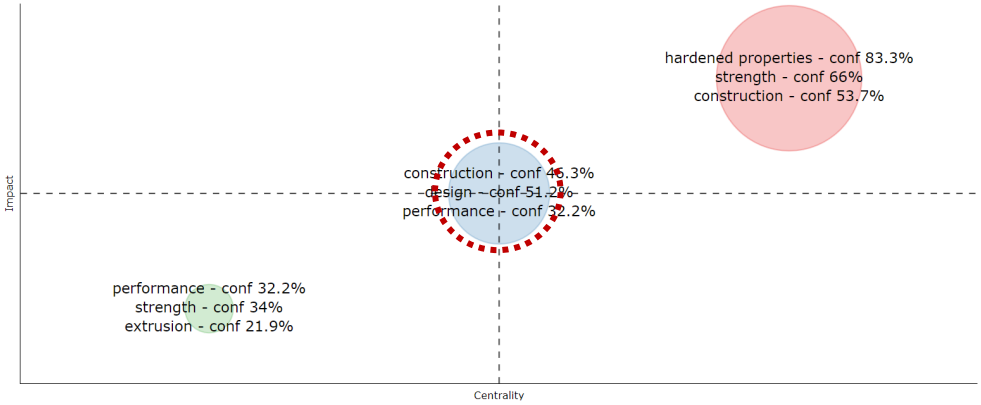


Fig. 8. Clustering by coupling (Biblioshiny)

Although the red group represents the largest group, the blue group constitutes the most important cluster group in this set of relationships. To summarise, in Fig. 8, it is understood that the studies on construction, performance and design are in the first group and represent important studies/keywords on the subject.

Table 2, to deepen the subject, the content of the 60 most cited articles among the 241 publications selected within the scope of the study has been classified into three different categories: construction, performance and design, which are prominent in the keywords. This classification provides a more in-depth analysis by identifying the articles' main research topics and areas of interest. Table 2 presents data on the content of the top 60 most cited publications. The number of articles selected (60) was determined by the aim of obtaining a deeper output by analysing the content of the publications in a wide range of publications. According to Table 2, publications between 1-21 are categorised under the title 'construction', publications between 22-55 under the title 'performance' and publications between 56-60 under the title 'design'. According to the analysis, %35 of the studies were on Construction, %57 on Performance and %8 on Design. The research methods of the studies were divided into three categories: 'experimental research (ER), literature review (LR) and review information supported (RIS)'. It was seen that the most commonly used method was 'experimental research (ER)'.

While analysing the contents of the publications in Table 2, they were divided into three groups. The 'Clustering by Coupling' analysis shown in Fig. 8 was decisive in determining this distinction. The three main titles determined for the content analysis can be defined as follows within the scope of the subject. Construction consists of articles that investigate the features that affect the constructability of 3DCP applications. Performance consists of articles about the steps towards the process after the completion of the product/structure. Design, on the other hand, consists of studies on the design of the structure/product in 3DCP applications.

The first title for the content analyses is 'Construction'. The publications in this section (1-21) mainly provide data on the process's research, design, application and method development for products produced with 3D printing technology in the construction sector. When the contents of this section are examined, the keywords 'Mix Design, Printability, Buildability, Rheological Properties, 3DPC applications' come to the fore. The second title analysed is 'Performance'. The publications in this section (22-55) consist of topics that are studied on the basis of the topics related to the title of 'Construction' and in relation to each other and include research on the development direction of the method.

Table 2. Classification of the top 60 most cited articles by subject

Subject	Ref.	Keywords/Focus	R. Method			Subject	Ref.	Keywords/Focus	R. Method		
			ER	LR	RIS				ER	LR	RIS
Construction	[31]	Buildability, Economic viability	❍			Performance	[36]	Large-scale additive manufacturing, Sustainable concrete	❍		❍
	[32]	Mix Design, Printability		❍			[58]	Ultra-high ductile concrete, Mechanical anisotropy	❍		❍
	[33]	Mix Design, Printability		❍			[59]	Mechanical property, Pore structure	❍		❍
	[29]	Mix Design, Buildability, Fresh properties	❍				[60]	In-process reinforcement, Interlayer bonding	❍		❍
	[34]	Mix design, Yield stress, Robustness, Test methods	❍				[61]	Hardened properties, Void distribution, Anisotropy	❍		
	[35]	3dpc, Thixotropy, Harden property, Anisotropy	❍				[62]	Bond strength, Thixotropy	❍		
	[36]	Rheological Properties, Buildability	❍				[63]	3DCP, Reinforcement, Bar penetrations, Pull-out strength	❍		
	[37]	Rheological Properties, Buildability, Vibration	❍				[64]	3DCP, Mesh Reinforcement, In-process embedment, Overlapping reinforcement	❍		❍
	[38]	3dpc technical, economic and environmental situation		❍			[65]	UHPFRC., Mechanical properties, Anisotropy	❍		❍
	[39]	Particle-bed 3D printing techniques		❍			[66]	Print-time interval, Inter-layer strength	❍		
	[40]	3dpc, Large-scale, on-site application, Construction management	❍				[67]	Hardened concrete, Bond strength, Interlayer adhesion	❍		❍
	[28]	Buildability, Analytical modelling, Rheology	❍				[68]	Reinforced concrete, Flexural behaviour	❍		❍
	[41]	Buildability, Yield stress, Mohr-Coulomb failure criterion	❍		❍		[69]	Digital concrete construction, 3D-printed steel reinforcement	❍		
	[42]	3dpc's potentials, Large-scale buildings		❍	❍		[70]	3dpc, Rheology, Thixotropy	❍		❍
	[43]	3dpc, Large-scale fabrication, Printability		❍			[71]	Rheology, Mechanical behaviour, Durability, Sustainability		❍	
	[16]	Extrusion, Rheology, Hardened properties, Geometric conformity	❍				[72]	Recycled sand, Hardened properties	❍		❍

Table 2. Cont'd

	[44]	3D printing concrete, Interlayer interaction, Interlayer strength, Molecular dynamics			❍		[73]	Extrusion-based, Coarse aggregate, Printability, Direction-dependent strength, Voids Interlayer area, X-CT, SEM	❍		❍
	[45]	3dcp, Additive manufacturing, Extrusion-based 3D printing		❍			[74]	3DPC, Recycled coarse aggregate Pore structure Anisotropic X-CT	❍		❍
	[46]	3DP, Recycled coarse aggregate, Rheology, Buildability	❍				[75]	3DPC XRD analysis Semi-adiabatic calorimeter SEM and EDX analysis Ultra-sonic activation	❍		
	[47]	Concrete technology, Additive manufacturing, Analytical modelling, Numerical simulations	❍		❍	Performance	[76]	Porosity, Compressive strength, Flexural strength	❍		❍
	[48]	3dpc, application, challenges		❍			[9]	Sustainability, Low carbon binder, Low energy binder		❍	
Performance	[49]	Mechanical properties, Rheology, Sustainability	❍				[77]	3DCP, Additive manufacturing, Bond shear strength, Flexural strength, Fibers	❍		❍
	[50]	3D concrete Interfacial bonding Frost resistance Polymers Air entrainer	❍		❍		[78]	Rheological properties, Structural build-up, Permanent formwork, 3DCP, Concrete column	❍		❍
	[51]	Digital fabrication, Concrete 3DP, Compression tests, Testing procedures, Failure prediction	❍		❍		[79]	LCA, environmental impact, sustainable construction			❍
	[52]	Mechanical properties, Flexural strength			❍		[80]	3DPC, Elevated temperature, Recycled sand, Mechanical behaviour, Microstructure	❍		❍
	[53]	Fresh concrete, Mechanical properties, Finite element modelling	❍		❍		[81]	Bespoke columns, Concrete prefabrication, Concrete automation	❍		❍
	[54]	Re-utilisation of solid resources, sustainability	❍			Design	[82]	Shell structure, Adaptable mould	❍		❍
	[55]	Fresh concrete, Mechanical properties	❍				[83]	Masonry, Cantilever, Vaults	❍		❍
	[56]	Structural failure Parametric, Optimisation	❍				[84]	Volume forming, Variable nozzle, Architectural ornament	❍		❍
	[57]	Rheology, Flow, Yield stress			❍		[85]	Topology optimisation, Bridge design	❍		❍

This section mainly includes details on the constructability, mechanical properties, strengthening and performance enhancement of products manufactured with 3DP technology and the development of sustainable approaches for the future. The keywords 'Mechanical properties, Sustainability, Reinforcement, Hardened properties' come to the forefront when we look at the focussed topics of this section. The last title that stands out in the content analyses is 'Design'. The number of articles here (56-60) is the section with the least clustering. There are mainly studies on designing and manufacturing building components (column, shell structure, masonry, bridge) at the last stage of 3DP technology. As 3DCP is an emerging trend, researchers continue to explore this technology by testing its geometrical and structural potentials [30]. The main focus of the studies on this topic is to investigate the different application potentials for design at the point where 3DCP technology has arrived.

When the contents of the studies are analysed (Table 2), it is understood that the studies on construction progress simultaneously with the studies on performance. Literature studies and experimental studies of applications support each other and reveal the still-developing structure of the subject. Studies on performance are generally experimental and include applications in the laboratory environment, and it is seen that this situation creates an infrastructure for large-scale construction applications. Compared to Construction and Performance, it can be said that there are relatively fewer studies on Design. The studies on design will likely increase in the future with the expansion of the application areas and possibilities of 3DCP. As a result, it can be said that there is a strong relationship between construction, performance, and design issues and that there is important potential in determining future research areas.

Fig. 9 shows the distribution of the articles (the 60 most cited articles) specified in Table 2 according to years. According to Fig. 9, the number of publications in 2018 and 2019 is 11, in 2020 is 17, in 2021 is 18, and in 2022 is 3. The distribution of the number of publications by years shows an increasing trend (except for 2022). This increase is thought to be due to the dynamic and developing structure of the subject in the literature. In addition, as can be seen in Fig. 2, the general increase in the number of publications on the subject makes a positive contribution to this output.

Table 3 summarises the opportunities and challenges for 3D concrete printing (3DCP) as derived from the content analysis. This table helps us to understand the potential and current challenges of 3DCP by providing a clear picture of its advantages and barriers.

4. Discussion and Conclusion

In this study, the bibliometric analysis method was used to identify, select, evaluate and systematise the research literature on 3DCP technology in construction manufacturing for the purpose of the study and to create new perspectives for future studies.

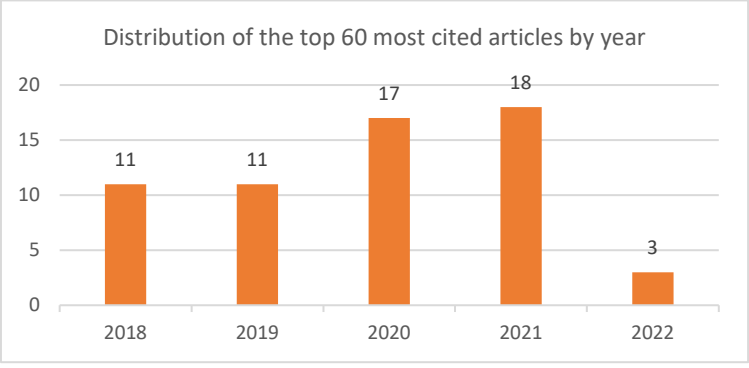


Fig. 9. Distribution of the top 60 most cited articles by year

Table 3. Challenges and potentials of 3DCP

	Challenges	Potentials
Construction	i. 3DCP applications require careful attention to project parameters and material properties for a successful outcome [32-34]. Ongoing research focuses on optimising printing materials and concrete mixes [48, 86]. ii. The development of design guidelines has been emphasised as important for the widespread applicability of 3DCP technology [32]. Studies and standards for concrete mixes in 3DCP technology still need to be sufficient. There are important studies on these mixtures in the literature in recent years [32-34].	i. Constructing buildings and structural components using 3DCP offers significant advantages over conventional construction methods [87]. ii. 3DCP provides advantages such as low cost, high efficiency in automated construction, and freedom of design [87]. iii. 3DCP technology increases cost efficiency in construction processes [38]. iv. Purposeful digitisation and automation of all the necessary steps from design and planning to the construction process is a viable solution to overcome these challenges in the construction industry, which are caused by low productivity and an increasing shortage of skilled labour [40].
Performance	i. The rheology of concrete plays an important role in concrete 3DP applications, where concrete is pumped at high pressure and extruded through a nozzle at low speed to form the structural component. ii. 3DP technology requires precise solutions in the process, linked to various parameters such as the scale of the project, the choice of printing materials, and the quality and strength of the post-printed parts [48, 86, 87].	i. Decisions made at the material production stage are important to increase the sustainability potential of 3D concrete printing applications [9]. ii. 3DCP applications are considered a possible alternative to traditional concrete construction due to their potential to increase productivity, reduce the environmental impact of the construction industry, and provide environmental benefits compared to traditional structures by conducting life cycle assessment (LCA) studies [79]. iii. With 3DP, complex geometries increase with design optimisation in the production of the building component, while at the same time, the use of concrete material produced is reduced. Thanks to this situation, the concrete material produced by 3D printing for structures with the same functionality performs better environmentally over the entire service life than conventionally produced concrete structures [38].
Design	i. The size of 3DP machines limits the size and scale of the structures that can be printed. 3DCP is limited in the number of storeys that can be built compared to traditional construction techniques. ii. Failure to correctly set the printer's parameters leads to final products with varying geometries.	i. 3DP technology provides much geometrical flexibility and diversity in the production of structures and building components compared to conventional methods. ii. This technology allows for non-traditional design methods such as optimisation of topology [85]. iii. While flexible geometries are produced with design optimisation in the production of the building component, the use of concrete material produced is also reduced, thus allowing cost reduction [38, 85]. iv. The relationship between studies on environmental performance and design also provides important data on the potential in this field. It is thought that studies on the design and implementation of structures and building components produced with 3DCP in the construction sector will become important in determining the direction of future studies.

The study used the Web of Science (WoS) Core Collection database to collect data. Analyses for 241 publications were obtained through Vosviewer and Biblioshiny databases. Looking at the studies on three-dimensional concrete printing technology in the field of engineering and architecture in the last six years, from 2018 to the present, it is seen that there is a continuous increase.

Looking at the number of publications made by countries on the subject, it was seen that China has

the highest number of research and is the most cited country. As a result of the bibliometric analysis of three-dimensional concrete printing technology in building production, it is seen that research and development research are gathered in two clusters. At this point, it is seen that the most basic keywords in the two cluster analysis are 'construction, performance and design'. The content of the 60 most cited articles among the 241 publications selected within the scope of the study was analysed in three different categories, namely 'construction, performance and design', which stand out in the keywords. This categorisation allowed for a more in-depth analysis by identifying the articles' main research topics and areas of interest. In conclusion, there is a strong relationship between the three topics identified, and they have important potential in identifying future research areas.

The points focused on in the titles for content analysis are as follows:

• Construction: It mainly provides data on the research, design, application and method development of the process for products produced with 3D printing technology in the construction sector.

• Performance: This focus area includes studies on the buildability, mechanical properties, and strengthening performance of products produced with 3DP technology, as well as the development of sustainable approaches for the future.

• Design: At the last stage of 3DP technology, there are mainly studies on the design and manufacturing of building components (such as columns, bridges, vaults, and walls). The main focus here is to investigate different application potentials for the design of this technology in its current state.

The Architecture, Engineering and Construction (AEC) industry has long been looking for new methods to reduce project costs, increase productivity and quality, reduce delivery time, automated processes, etc. [88]. 3DCP technology is a technology that has significant potential for the expectations of the AEC industry in this direction and its use in the sector is increasing day by day. On the other hand, this technology is still developing and used for a limited number of application areas [89]. In this context, it is important to increase the studies and awareness on the subject. In this study, which aims to evaluate the current status and potential of 3DCP technology in the AEC (architecture, engineering and construction) industry, it has been observed that this technology is still an emerging field and that there is a need for further research and application in the 'design' of the subject in terms of the AEC sector. The study will likely provide important references in terms of processes and trends in the sector.

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Author Contributions

Ş. Gebel: Conceptualization, Methodology, Investigation, Writing-Original draft, Writing-Reviewing and Editing,Visualization. S. M. Top: Writing-Original draft, Methodology, Investigation, Writing-Reviewing and Editing. Ç. Takva: Writing-Original draft , Writing-Reviewing and Editing. B. İ. Gökgöz: Writing-Original draft, Writing-Reviewing and Editing. Z. Y. İlerisoy: Conceptualization, Writing-Review and Editing, Supervision, Project administration. M. Şahmaran: Writing-Review and Editing.

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Not applicaple.

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