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## INTELLIGENT TOOLS FOR LARGE-SCALE 3D PRINTING: A SCOPING REVIEW

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### Abstract

*In recent decades, building methods such as 3D printing have been increasingly researched for the design and fabrication of various architectural elements. Artificial Intelligence is another rapidly developing technology whose potential in the building industry is continuously being explored. This paper's objective lies in mapping out the field of existing Artificial Intelligence tools for large-scale 3D printing, searching for possible applications throughout the different development stages including the pre-fabrication phase with structural design, optimization, behavior simulations, and predictions, as well as the production phase through the real-time monitoring of the process. In this study, different types of Artificial Intelligence (such as machine learning, deep learning, and computer vision), have been identified regarding their role in 3D printing to assess its potentials, limitations, and the present research gaps. Finally, potential research directions and emerging topics are presented. The study's findings increase the understanding of Artificial Intelligence techniques and applications in the 3D printing process and can aid in choosing and implementing the most promising ones in further research.*

**Key words:** Artificial Intelligence, Additive Manufacturing, 3D Printing, Digital Fabrication, Architecture Design

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## 1. INTRODUCTION

According to existing research, the limitations of 3D printing (3DP) methods and their application in the building industry, such as excessive time consumption, the inability to control the printing process in real-time, a lack of building consistency, imperfections in the printed parts, and others, could be addressed by incorporating Artificial Intelligence (AI) into the design and manufacturing process [1, 2]. Most often, AI is understood as a set of diverse computer algorithms that are capable of learning, reasoning, self-correction, and rational thinking, in a similar way that the human mind does [3]. The most researched types of AI in the Architecture, Engineering, and Construction (AEC) sector, among others, include genetic and evolutionary algorithms, neural networks, fuzzy logic, machine learning, computer vision, particle swarm optimization, deep learning, and expert systems [4]. Additive Manufacturing (AM) is a method of creating 3D objects by the layering of material [5]. Large-scale 3DP, a subset of AM methods, has the potential to allow the fabrication of non-standard elements on the building construction scale. Generally, binder jetting and material deposition method (MDM) are the two primary technologies utilized for large-scale 3DP [6].

A rapidly growing body of research can be found on the use of AI in the Architecture, Engineering and Construction Industry (AEC) [4, 7–10], as well as the phenomenon of AI-aided 3DP [11–13]. However, it was determined that there is still insufficient systematization and overview of available data needed to understand current trends and potential in the field. For this reason, this study presents a scoping review integrating both topics.

This study maps out the literature that is presently accessible on AI in large-scale 3DP and assesses the nature of the underlying ideas and techniques employed, to identify topics for future research. The research methodology is guided by affirmed frameworks [14, 15]. The main research question is pointed at the potential of different AI tools in large-scale 3DP. To answer this, a defined protocol is used which includes a systematic search strategy based on the information that can be obtained in the Web of Science (WoS) database, inclusion, and exclusion criteria for the study selection, and established criteria for the analysis of the sources of evidence. Next, a data charting procedure is established, a summary of the charted data, and conclusions are derived from the study. The contribution of this study lies in the research guided towards the presentation of key concepts and characteristics of the AI techniques and tools in 3DP technology used for large-scale applications, identification of the knowledge gaps, and informing future research on specific topics.

## 2. METHODOLOGY

Scoping reviews are an evolving means of informing decision-making and research that is based on the identification and examination of the literature on a particular subject or problem [15]. The primary distinction between systematic literature reviews and scoping reviews is that the former is highly specialized in an in-depth analysis of a particular research subject, whereas the latter is used to

provide an overview perspective on general issues relating to the topic of interest. Because of this, a scoping review methodology was selected as suitable for this study covering a broad field of research.

## 2.1. Search strategy

As indicated in Figure 1, the search method is carried out using keywords and operators in the electronic Web of Science database. The search was limited to categories including Civil Engineering, Construction & Building Technology and Architecture, to get the relevant results. The papers that were chosen were published after 2013.

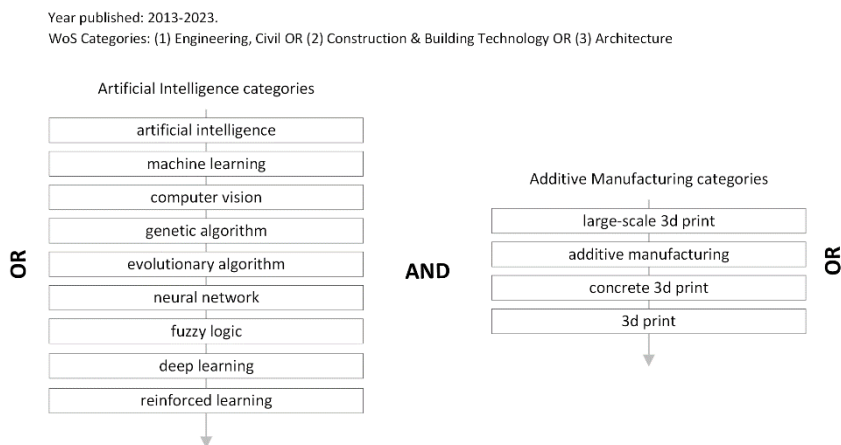


Figure 1. Keywords and operators used for the online database

This approach yielded a total of 64 results, which represent the primary pool of literature to be narrowed down using inclusion and exclusion criteria.

## 2.2. Data selection

After the initial search, the collected sample of literature was further assessed and filtered based on the topic, relevance, and full paper accessibility. The next step in the selection phase is the screening of the papers by reviewing the abstracts and eliminating papers that do not fall into the building science category or are not relevant to the research topic, which represents the main exclusion criteria. An important factor during the screening process is the focus of the screened papers on the specific correlation of AI and 3DP, not the processes separate. Finally, full texts were reviewed eliminating a number of papers based on the relevance to the research. The screening process left the selected papers at 14, as shown in Figure 2. The purpose of reading full articles was to develop insight and comprehension of the underlying concepts in the examined papers, providing the material for associated charts. In order to avoid selection bias the collection and screening were done as a two-step process with two researchers simultaneously screening the selected sample after the initial search and cross-checking the remaining selection while the third researcher was responsible for overseeing the process.

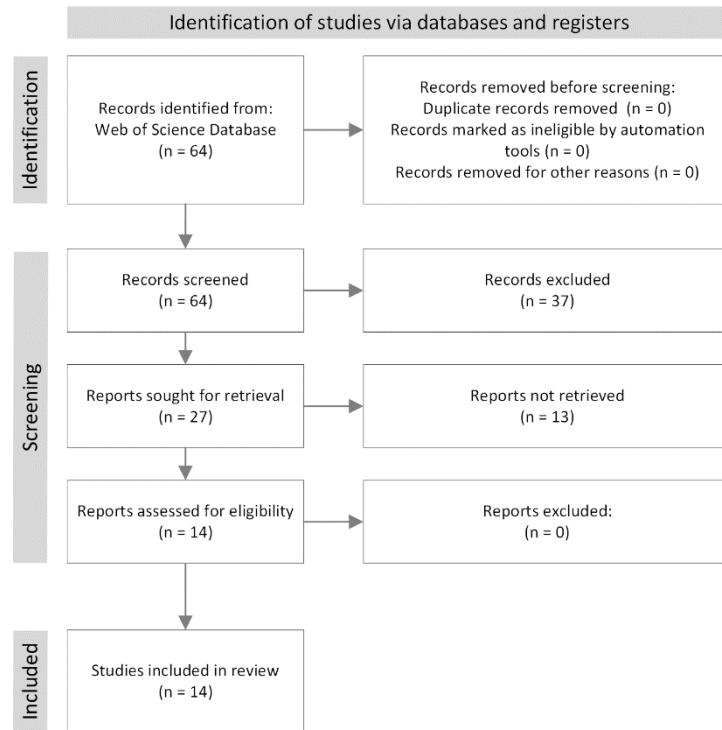


Figure 2. Flow diagram of the literature screening process

Among the selected papers, 4 are in the form of conference papers, and the remaining 10 studies are journal articles. Conferences and journals that were the source of selected papers are represented in Figure 3.

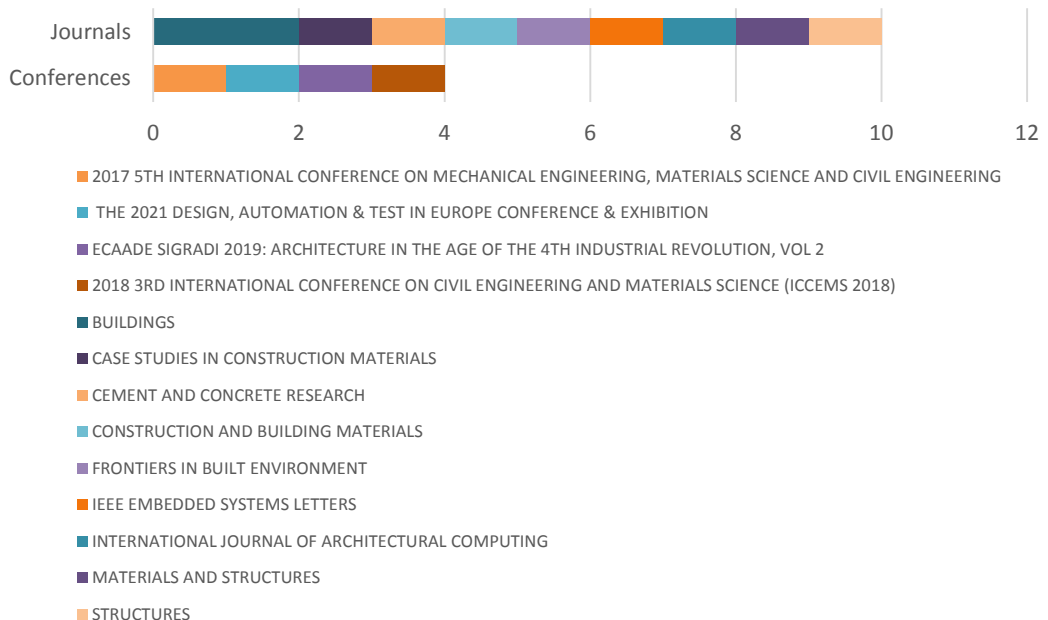


Figure 3. Names of the source conferences and journals

### 2.3. Data charting criteria

The data charting approach was used to discover the fundamental principles in the use of AI methodologies and tools in 3DP technology. This corresponds to the main purpose of this study, which is to acquire a broad picture of the potential of present and future applications and collaboration of the technologies discussed. The major purpose of the charting procedure is to highlight significant principles underlying the introduction of AI in the 3DP process, the main AI tools and methodologies, the function of AI in the design and manufacturing process, as well as the main findings and guidelines that the authors of the research have pointed out.

## 3. RESULTS

The research findings were summarized in three key aspects that together provide an overview of the concept of collaborative AI usage and 3DP: (1) the main AI tools and methods used, (2) the main applications and roles of AI supporting the 3DP process, and (3) key research findings regarding the challenges and benefits of the represented methods and techniques, as shown in Table 1.

*Table 1. Summary of the main AI tools and methods, applications, and research findings*

Paper	AI tools and methods	Applications and roles	Findings
[16]	Computer vision Deep convolutional neural networks	Geometrical accuracy measurements for 3DP elements	AI models are reliable in design variation detection and provide a feedback control system to automatically adjust the material deposition
		Automated layer detections	
[17]	Computer vision	Image-based object tracking	AI models are effective in tracking key features of the 3DP model
[18]	Machine learning	Conceptual design	A small amount of research of AI in 3DP is conducted in the building industry
		Design optimization	
		Geometry deviation prediction	
		Material analytics	
		Defects prediction	
[19]	Multi-objective optimization	Final product performance prediction	AI aids in developing a performance-based iterative design of 3DP elements
		Performance-based façade panels design	
[20]	Machine learning Computer vision	Timely detection of powder bed defects	The discovered issue relates to the imprecision in the image capture timing; The spattering identification algorithms have difficulty between similar defects; The process is not time consuming, except for

			normalization and active contouring
[21]	Machine learning Conditional generative adversarial networks	Performance prediction	Neural networks have potential to integrate analytic and predictive information in real-time design and fabrication processes
		Rapid structural analysis based on unstructured point clouds	
[22]	Artificial intelligence in general	Sensor informed augmentation of the logic of 3DP processes	Not specific towards 3DP process
[23]	Machine learning	Detection of compromises in g-codes without having access to original models	Machine intelligence algorithms reduce the accuracy, therefore need to be trained and refined further
[24]	Artificial neural network	Quality control of material structural performance	The algorithm accurately predicts the structural properties; The neural network validly represents the relationship between input parameters and predicted properties
[25]	Computer vision	Online real-time extrusion quality monitoring	Computer vision is the most reliable and responsive technique for detecting printing material variations, compared to other techniques
[26]	Supervised learning Unsupervised learning Semi-supervised learning Reinforcement learning	Accurate material performance prediction	For material design, the application of machine learning can improve construction production efficiency and save construction costs
		Printing control through prediction models	
		Quality inspection of construction components	
[27]	No specific tool or method applied	Automated construction in 3DP in harsh environments	Current automation systems only apply on concrete materials in domain of 3DP
[28]	Deep learning	Automatic segmentation of x-ray scans of 3DP samples	Deep-learning segmentation method from the Dragonfly software was successfully used to extract the distribution of steel fibers inside the 3DP specimens
[13]	Machine learning Pattern recognition Computer vision	Material selection, optimization, quality assessment	AI and Building Information Modelling (BIM) combined could lead to resolving multiple problems and challenges faced in 3DP
		Predicting economic benefits	

		Revising construction schemes	
		Optimizing 3DP robots, path planning	

## 2.1. AI techniques and applications in large-scale 3DP

The applied AI approaches are largely affected by their involvement in the 3DP process. Machine learning algorithms [13, 18, 20, 21, 23] have sub-variations in reinforced, semi-supervised, supervised, unsupervised [26], and deep learning [28], each with various capabilities and applications. Artificial neural networks [24], with variants in conditional generative adversarial networks [21] and deep convolutional neural networks [16], are the other most often used AI technologies. Computer vision [13, 16, 17, 20, 25] is another frequently employed approach in the reviewed study, with a sub-variation in pattern recognition [13].

The applications of AI can be found in different stages of the 3DP process, from design, through fabrication, to monitoring and evaluation of the manufactured parts. With the application of AI in the design for manufacture process, the conceptualization of constructions has the potential of becoming an iterative process that considers the specific manufacturing process limits and challenges [21]. This cohesion between technologies allows for the performance-based design strategy which aims at refining the initial designs to suit best the given environmental characteristics [19]. In the production phase, it is possible to establish a relationship between the digital models of the structure and the real-time extrusion process, altering the process if defects occur [16, 20, 25], as well as create accurate predictions on the material, structural and visual properties of 3DP elements and structures [21, 24, 26, 29]. The evaluation phase is mostly connected to computer vision algorithms which detect the anomalies in the printed parts [18, 26].

## 4. DISCUSSION

The study presents numerous relevant discussion points about the application of AI in large-scale 3DP construction. The first point highlights the gap in the number of papers discovered on different AI methodologies, with machine learning and computer vision dominating, while research on the application of evolutionary and genetic algorithms is less prevalent. Eleven of the evaluated publications focused on investigating machine learning tools, six on computer vision, and the remainder on other types of algorithms, as shown in Figure 4.

The second point relates to the stage at which AI is introduced in the 3DP process, where the studies dealing with print quality control prevail, and cost analysis is the least researched topic. Having in mind that large-scale 3DP applications are conceptually tied to the industrial sector, these topics should be of interest for future research, to enable timely integration in the building industry. The main concepts of application of AI found in the researched papers are represented in Figure 5.

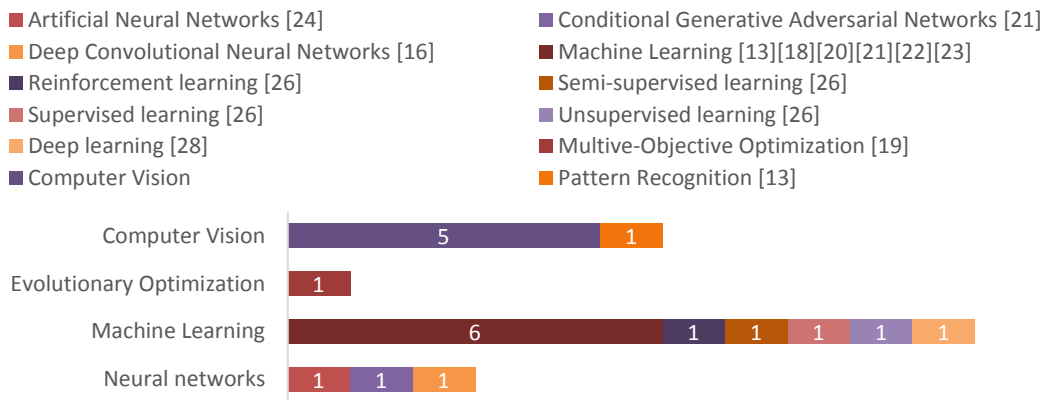


Figure 4. AI tools and methods. Paper reference stated in the square brackets.

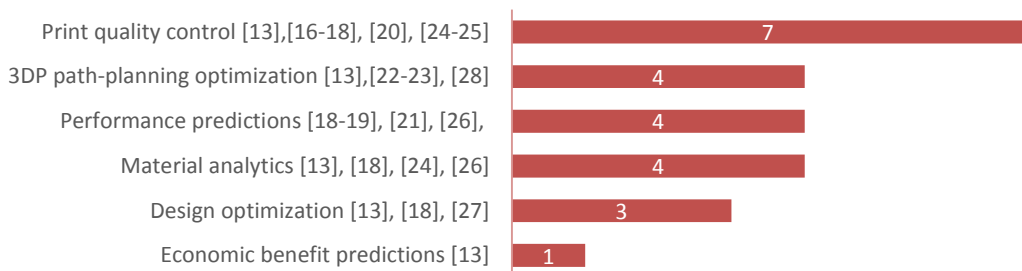


Figure 5. Applications of AI in 3DP. Paper reference stated in the square brackets.

As illustrated in Figure 6, this study emphasizes several potentials and problems uncovered during the literature assessment to select the areas most significant for prospective applications and research. One of the biggest challenges with deploying AI techniques such as deep learning and machine learning is the amount of data necessary to properly train the algorithms so that they can retrieve relevant and accurate data. The application is more complex because of the large computer power this technique generally requires. The 3DP processes have mostly been investigated in laboratory settings and for small-scale applications, and it has been acknowledged that more research is needed in the fields of building applications and real-world assessments. The papers evaluated largely deal with concrete or steel 3DP applications, limiting the conclusions to their qualities and ignoring a substantial portion of 3DP potential uses. A research gap in the study of sustainability and carbon emissions has been identified. Although some studies indicate the current development of research aiming at the reconstruction and conservation practice of architectural heritage utilizing sensing technologies in cooperation with 3DP, little evidence of such study exists in the examined literature. Several publications emphasize the need to evaluate computer vision approaches in real-world contexts, such as building sites, while keeping in mind the variations that may prevent such algorithms from operating in such conditions (such as differing light settings). The goal of applying AI logic to the 3DP process should be guided towards solving several key challenges that were posed with this technology, with emphasis on the problems that could be more efficiently resolved with computer intelligence, instead of using traditional methods.



It is important to keep in mind that the technology that is to be used on large-scale applications should at some point become profitable and accessible, which isn't currently the case in 3DP. Another challenge that is posed for the engineers and other professionals involved in the building process is the ability to use the AI tools, bearing in mind they are not trained or educated to use such tools. An important emphasis should be put on developing methods and tools which could be accessible to individuals outside of the academic environment, for it to be most efficiently integrated into current building methods.

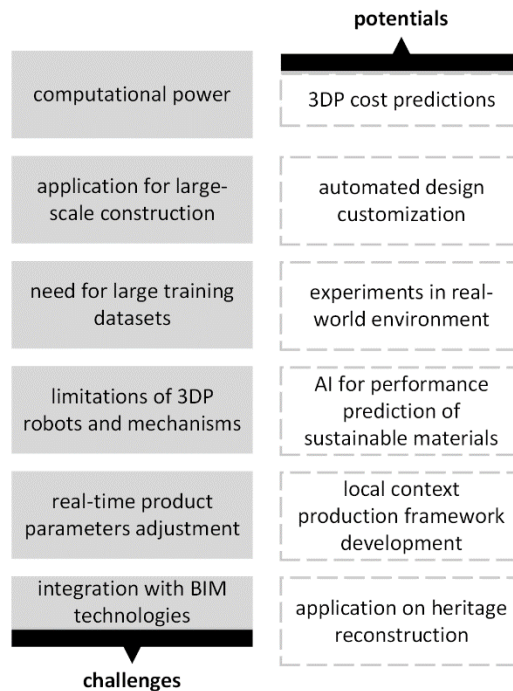


Figure 6. Potentials and challenges that accompany AI in large-scale 3DP

## 5. CONCLUSION

The study reviews and addresses applications and domains of AI in the large-scale 3DP design and manufacturing processes, highlighting specific underlying concepts that arise in the reviewed research. The methodological procedure was displayed, including the search strategy, data selection criteria, and charting procedure. Additionally, a PRISMA flow diagram of the selection process, as well as the main sources from which the selected papers originated have been shown. The main AI tools and methods, applications, and challenges have been identified and systemized. The several most often employed techniques have been identified and discussed, such as machine learning and computer vision, mainly used for defect detection in the printing process. Research regarding the direct linkage of the design process with parameters adjustment, and the fabrication process is less frequent in the context of AI techniques and therefore represents an important consideration for future research.

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## REFERENCES

- [1] Yang Jimeng, Chen Yi, Huang Weidong, Li Yun: **Survey on artificial intelligence for additive manufacturing**. *23rd International Conference on Automation and Computing (ICAC)*, Huddersfield, 1-6, 2017.
- [2] Jin Zeqing, Zhang Zhizhou, Demir Kahraman, Gu Grace X.: **Machine Learning for Advanced Additive Manufacturing**. *Matter*, Vol. 3, No. 5, 1541–1556, 2020.
- [3] Kok Joost N., Boers Egbert J. W., Kusters Walter A., Van der Putten Peter, Poel Mannes: **Artificial Intelligence: Definitions, Trends, Techniques, and Cases**. *An Insight into the Encyclopedia of Life Support Systems*. UNESCO Publishing/EOLSS Publishers, Oxford, 1095-1107, 2002.
- [4] Darko Amos, Chan Albert P.C., Adabre Michael A., Edwards David J., Hosseini M. Reza, Ameyaw Ernest E.: **Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities**. *Automation in Construction*, Vol. 112, 103081, 2020.
- [5] Saleh Abd Elfatah Ahmed: **3D Printing in Architecture, Engineering and Construction (Concrete 3D printing)**. *Engineering Research Journal*, Vol. 162, No. 0, 119–137, 2019.
- [6] Žujović Maša, Obradović Radojko, Rakonjac Ivana, Milošević Jelena: **3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review**. *Buildings*, Vol. 12, No. 9, 1319-1343, 2022.
- [7] Emaminejad Newsha, Akhavian Reza: **Trustworthy AI and robotics: Implications for the AEC industry**. *Automation in Construction*, Vol. 139, 104298, 2022.
- [8] Zhang Fan, Chan Albert P.C., Darko Amos, Chen Zhengyi, Li Dezhi: **Integrated applications of building information modeling and artificial intelligence techniques in the AEC/FM industry**. *Automation in Construction*, Vol. 139, 104289, 2022.
- [9] Emaminejad Newsha, North Alexa Maria, Akhavian Reza: **Trust in AI and Implications for AEC Research: A Literature Analysis**. *Computing in Civil Engineering: American Society of Civil Engineers*, Orlando, 295–303, 2022.
- [10] Mohammadpour Atefeh, Karan Ebrahim, Asadi Somayeh: **Artificial Intelligence Techniques to Support Design and Construction**. *36th International Symposium on Automation and Robotics in Construction*, Banff, 2019.
- [11] Goh Guo Dong, Sing Swee Leong, Yeong Wai Yee: **A review on machine learning in 3D printing: applications, potential, and challenges**. *Artificial Intelligence Review*, Vol. 54, No. 1, 63–94, 2021.
- [12] Dechen Chen, Luo Dan, Xu Weiguo, Luo Chen, Yan Xia, Shen Liren, Wang Tianjun: **Re-perceive 3D printing with Artificial Intelligence**. *Blucher Design Proceedings*, Porto, 443–450, 2019.
- [13] Tan Kang: **The Framework of Combining Artificial Intelligence and Construction 3D Printing in Civil Engineering**. *MATEC Web of Conferences*, EDP Sciences, 2018.

- [14] Tricco Andrea C., Lillie Erin, Zarin Wasifa, O'Brien Kelly K., Colquhoun Heather, Levac Danielle, Moher David, et al.: **PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation**. *Annals of Internal Medicine*, Vol. 169, No. 7, 467–473, 2018.
- [15] Peters Micah D.J., Marnie Casey, Tricco Andrea C., Pollock Danielle, Munn Zachary, Alexander Lyndsay, McInerney Patricia, Godfrey Christina M., Khalil Hanan: **Updated methodological guidance for the conduct of scoping reviews**. *JBIM Evidence Synthesis*, Vol. 18, No. 10, 2119–2126, 2020.
- [16] Mechtcherine Viktor, Van Tittelboom Kim, Kazemian Ali, Kreiger Eric, Nematollahi Behzad, Naidu Nerella Venkatesh, Santhanam Manu, et al.: **A roadmap for quality control of hardening and hardened printed concrete**. *Cement and Concrete Research*, Vol. 157, 106800, 2022.
- [17] Baruah Angshuman C., Sychterz Ann C.: **Assessment and Comparison of Cable-Actuation of Pill Bug Inspired Adaptive Origami Structure Using Computer Vision and Dynamic Relaxation**. *Frontiers in Built Environment*, Vol. 8, 843543, 2022.
- [18] Tuvayanond Wiput, Prasittisopin Lapyote: **Design for Manufacture and Assembly of Digital Fabrication and Additive Manufacturing in Construction: A Review**. *Buildings*, Vol. 13, No. 2, 429, 2023.
- [19] Giantini Guilherme, Negris de Souza Larissa, Turczyn Daniel, Celani Gabriela: **Environmental Ceramics Merging the digital and the physical in the design of a performance-based facade system**. *ECAADE SIGRADI 2019: Architecture in the age of the 4TH Industrial Revolution, Vol 2*. ECAADE-Education & Research Computer Aided Architectural Design Europe, Brussels, 749–758, 2019.
- [20] Cannizzaro Davide, Varrella Antonio Giuseppe, Paradisot Stefano, Sampierit Roberta, Macii Enrico, Patti Edoardo, Di Cataldo Santa: **Image analytics and machine learning for in-situ defects detection in Additive Manufacturing**. *The 2021 Design, Automation & Test in Europe Conference & Exhibition IEEE*, New York, 603–608, 2021.
- [21] Nicholas Paul, Rossi Gabriella, Williams Ella, Bennett Michael, Schork Tim: **Integrating real-time multi-resolution scanning and machine learning for Conformal Robotic 3D Printing in Architecture**. *International Journal of Architectural Computing*, Vol. 18, No. 4, 371–384, 2020.
- [22] Al Jassmi Hamad, Al Najjar Fady, Mourad Abdel-Hamid Ismail: **Large-Scale 3D Printing: The Way Forward**. *5th International Conference on Mechanical Engineering, Materials Science and Civil Engineering*, Vol. 324, Bristol, 2018.
- [23] Beckwith Caleb, Naicker Harsh Sankar, Mehta Svara, Udupa Viba R., Nim Nghia Tri, Gadre Varun, Pearce Hammond, Mac Gary, Gupta Nikhil: **Needle in a Haystack: Detecting Subtle Malicious Edits to Additive Manufacturing G-Code Files**. *IEEE Embedded Systems Letters*, Vol. 14, No. 3, 111–114, 2022.
- [24] Alhaddad Wael, He Minjuan, Halabi Yahia, Almajhali Khalil Yahya Mohammed: **Optimizing the material and printing parameters of the additively manufactured fiber-reinforced polymer composites using an artificial neural network model and artificial bee colony algorithm**. *Structures*, Vol. 46, 1781–1795, 2022.
- [25] Kazemian Ali, Khoshnevis Behrokh: **Real-time extrusion quality monitoring techniques for construction 3D printing**. *Construction and Building Materials*, Vol. 303, 124520, 2021.
- [26] Geng Songyuan, Luo Qiling, Liu Kun, Li Yunchao, Hou Yuchen, Long Wujian: **Research status and prospect of machine learning in construction 3D printing**. *Case Studies in Construction Materials*, Vol. 18, e01952, 2023.

- [27] Liu Kewei, Meng Qingfei, Kong Qingzhao, Zhang Xihong: **Review on the Developments of Structure, Construction Automation, and Monitoring of Intelligent Construction.** *Buildings*, Vol. 12, No. 11, 1890, 2022.
- [28] Chen Yidong, Zhang Yunsheng, Pang Bo, Wang Dafu, Liu Zhiyong, Liu Guojian: **Steel fiber orientational distribution and effects on 3D printed concrete with coarse aggregate.** *Materials and Structures*, Vol. 55, No. 3, 100, 2022.