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The Future of 3D Printing Technology in the Construction Industry: a Systematic Literature Review

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ABSTRACT

Technological changes have remarkable effect on today's business world that triggers industries to reestablish the production systems. 3D printing has evolved with the new technological developments in additive manufacturing over the last three decades. 3D printing technologies enable design optimization and have advantages over conventional production methods. All industries should adopt the new era in order to survive in a rapidly changing competitive environment. The construction industry is also under technological developments' pressure to change. Therefore, 3D printing technology is under a great attention in construction industry as a new strategic challenge. The construction industry takes 3D printing as an idea of a new building technology. The main aim of this paper is to review the 3D printing technology applications of other industries, to review 3D printing attempts in construction industry and to comment on possible application areas for 3D printing intentions in construction industry. This paper summarizes the literature on 3D-printing applications used in other industries, with a focus on adaption strategies in construction industry. Major literature databases are reviewed about 3D printing researches and the trials of implementations in construction industry. Collected data is interpreted in the construction research jargon. The possible implementation areas in construction are suggested for future developments. The paper results in identifying and classifying the new developments in 3D printing technology in various industries and making projections on the possible adaptation areas in construction industry.

Keywords: 3D printing technology, 3D printing applications, construction industry.

INTRODUCTION

Printing with a three-dimentional (3D) printer; is the process of converting objects modeled in the computerized environment into real objects in layers using the required raw materials. The 3D printer, seen as a complex and expensive technology in the years it was invented. However, it has been one of the most important facts of the industry over the years. Since 1983, the date Charles W. invented 3D printer, the new technology shows rapid developments and entered into every field of various industry, such as automotive, aerospace and space technology and medicine, today [1]. Tissue engineering and regenerative development have made it possible to print such organs or tissues with the help of bio-printers produced by 3D printing technology [2]. These achievements attract the attention of different industries and science fields about 3D printing technology. The 3D printing version of the concrete is currently being studied in the construction industry applications and academia [3]. Today, with advances in technology, it is possible to print engineering structures with a 3D printer

[4]. 3D printing has become an innovative and promising method, with an increase in use for cementitious material. The use of this printing technique in waste materials and recyclable materials is under investigation [5]. Nasa reveals that “we will not be able to get everything we need from our world for the habitats that will be created on the surface of the mars and moon, and even beyond, and the explorers who will go there. Because it is impossible to take all these conventional resources from our world, we are competing for technological ideas and innovative inventions to create structures that will enable the establishment of habitats that can be lived with 3D printers in places where we are going”. Nasa also has intensive activities in 3D concrete printing works [6]. In global and regional terms all countries and research groups that are effective in construction industry should change their focus on revolutionary innovations and technological developments for determination and management of models and methods to investigate and additional studies on 3D printing.

In this literature review reseach on 3D printing technology, local publications about concrete printing have been examined. In addition, publications on 3D printing technology applications with global scale are evaluated in all disciplinary fields. The work done by YÖK thesis screening center and TUBITAK Ulakbim for local studies is examined. The literature search was carried out via web of science for publications in the global scale,. PubMed is studied in the field of medicine. The future of 3D printing technology in the field of construction is discussed and suggestions are made for practioners, future works and the possible use areas in the construction industry.

MATERIALS AND METHODS

Studies on 3D printing field in Turkey are investigated. The YÖK Thesis Center Database is scanned for all existing theses. Literature search is done with the keyword “3D print”. Theses are examined according to their disciplines, titles and numbers. The "TUBITAK Ulakbim" database is scanned by including all the databases without any restrictions. Literature search; {3D & printer}@"Abstract" is done with the keyword. The publications are examined according to title and number.

Studies published in English language related to 3D printing field are investigated globally. The Web of Science database is scanned in all disciplines between 1983 and April 2018 years without any other restrictions. Literature search; is done with keyword TI = (3D printing). Articles and Proceedings Papers are scanned. The first 100 categories according to the number of records of the Web of Science scans were examined by years and discipline name. In order to examine 3D printing publications in terms of Civil Engineering and Construction Building Technology disciplines, more detailed scanning is done on Web of Science. Literature search; between 1983 and April 2018 years is done with the keyword TI=(3D printing), and Construction Building Technology and Civil Engineering fields are refined. The scan is done in English and only for article and prooceeding publications. Publications are evaluated in detail in terms of title, year of publication, authors and subjects.

In order to get a more detailed look at the studies done in the field of Medicine, PubMed scan is performed between 1983 and April 2018. Literature search; is done with keywords (3D printing[title/Abstract]) and medicine[title/Abstract].

RESULTS AND DISCUSSION

3d Printer Research in Turkey

In the screening of YÖK Thesis Center Database, twenty one theses are reviewed. Thesis Topics are presented in Table 1.

Table 1. The disciplines and themes of YÖK theses on 3D printer

Discipline	Thesis Title
Mechanical Engineering * Mechatronics Engineering	• Production and characterization of polymer nano composite filaments for 3D printers • Design and implementation of a 3D printer by using extrusion technique • Design and analysis of scar type 3D printer • Design and analysis of hybrid CNC router and 3D printer*
Engineering Science * Electrical and Electronics Engineering	• 3D printer design, prototyping and reverse engineering applications • Mechanical strength of 3D printed objects: Experimental and numerical investigation • Towards fully 3D-printed miniaturized confocal imager*
Energy	• 3D-printed multiprobe analysis system for solar fuel research; design, fabrication and testing
Metallurgical Engineering * Polymer Science and Technology	• Effects of glass fiber content, 3D-printing and weathering on the performance of polylactide* • A single additive for 3D printing of highly-concentrated iron oxide inks
Architecture	• Proposal for an innovative housing approach extraordinary situation by using 3D printing
Fine Arts * Clothing Industry	• The use of 3D printing technologies in the art of sculpture • The surface designs with 3D printers for fashion products*
Performing and Visual Arts	• 3D printing and using in cinema
Industrial Design * Mechanical Engineering, Polymer Science and Technology	• Double head cartesian type 3D printer design and prototyping (model from granule) • Composite part design with FDM 3D printer and investigation of mechanical properties* • Investigation of 3D printer by using mks sbase v 1.3 terms of control on the internet
Computer Engineering and Computer Science and Control	• Design new test model for 3D printers
No Show	• Modal analysis of 3D printed parts

Discipline	Thesis Title
Physical Medicine and Rehabilitation Oncology Radiology and Nuclear Medicine	• Quality control of micro-multileaf collimator based brain and head-and-neck intensity modulated radiotherapy plans with patient-specific phantom design and production using 3D printing technology
Orthopedics and Traumatology	• The effect of 3D printed spine model on surgical planning of complex spine deformities

*Multidisciplinary thesis study

Distribution of thesis by years is visualized in Figure 1. Thesis topics include a study in the field of architecture. The theses written in the field of 3D printing are increasing by years.

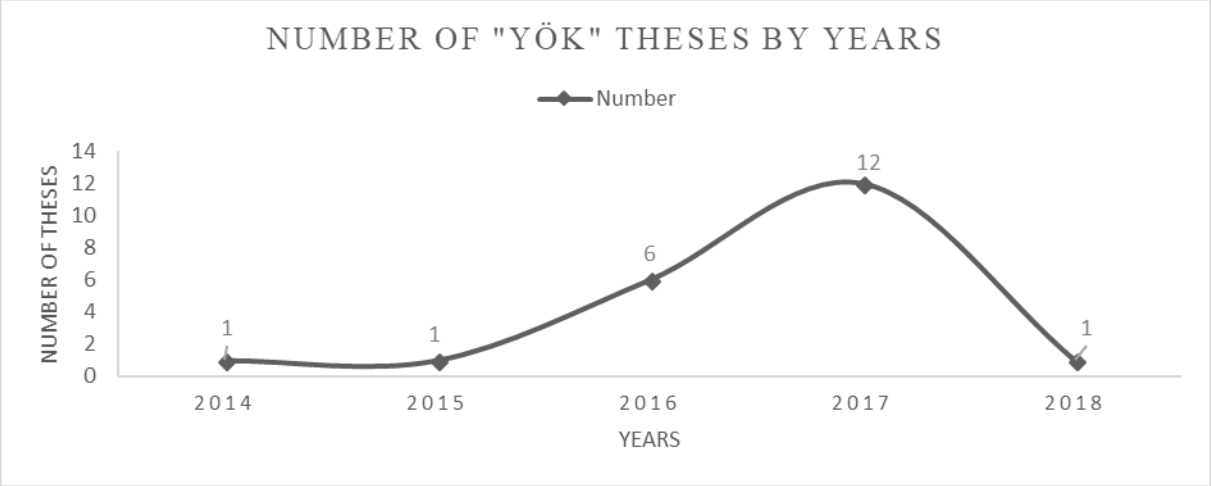

Figure 1. Number of "YÖK" Theses by Years

Three publications were published in "TUBITAK Ulakbim" database. Publication Topics are also given in Table 2. A study in the field of Civil Engineering has not been found.

Table 2. The database and titles of "TUBITAK Ulakbim" publications about 3D Printing

ULAKBIM Database	Publication Title
Engineering and Basic Science Database	• Design and development of high performance textile structures with 3D printer for composites • Design and Development of Patient-Specific Medical Orthosis with 3D Printer and Scanner
Social Science Database	• Principles of application in 3D printers and guests as a computer aided ceramic production method

3d Printer Studies on Global Scale

The web of science scan contains 3998 publications containing the word "3D printer" in the title. According to the first hundred Web of Science category which has the most publication, the number of publications is listed in Table 3. According to the number of studies that resulted in the search of Web of Science, the number of publications in the TUBITAK Ulakbim Databases are found to be less.

Table 3. Distributions of 3D printing titled articles and proceedings paper in Web of Science database

Web of Science Database	**Num.**	**Web of Science Database**	**Num.**
Materials science multidisciplinary	751	Computer science interdisciplinary applications	75
Engineering electrical electronic	706	Computer science software engineering	67
Physics applied	405	Biochemical research methods	66
Nano science nanotechnology	344	Engineering chemical	62
Engineering biomedical	306	Pharmacology pharmacy	61
Chemistry multidisciplinary	270	Education scientific disciplines	60
Engineering manufacturing	266	Computer science information systems	58
Optics	252	Energy fuels	55
Engineering mechanical	242	Electrochemistry	54
Materials science biomaterials	238	Dentistry oral surgery medicine	50
Telecommunications	168	Imaging science photographic technology	48
Multidisciplinary sciences	154	Biotechnology applied microbiology	47
Chemistry analytical	149	Metallurgy metallurgical engineering	46
Instruments instrumentation	148	Materials science ceramics	40
Chemistry physical	132	Orthopedics	40
Radiology nuclear medicine medical imaging	128	Materials science composites	39
Polymer science	122	Medicine research experimental	39
Engineering multidisciplinary	117	Cell tissue engineering	37
Automation control systems	116	Mechanics	35
Physics condensed matter	110	Biophysics	32
Computer science theory methods	99	Clinical neurology	30
Surgery	95	Computer science cybernetics	28
Robotics	89	Education educational research	28
Engineering industrial	87	Construction building technology	26
Computer science artificial intelligence	84	Remote sensing	26

Web of Science Database	**Num.**	**Web of Science Database**	**Num.**
Food science technology	25	Law	14
Management	24	Pediatrics	14
Operations research management	24	Information science library science	13
Cardiac cardiovascular systems	23	Neurosciences	13
Biochemistry molecular biology	22	Respiratory system	13
Engineering civil	22	Chemistry applied	12
Architecture	21	Critical care medicine	12
Green sustainable science	21	Humanities multidisciplinary	12
Otorhinolaryngology	21	Medicine general internal	11
Pyhsics multidisciplinary	21	Anatomy morphology	10
Cell biology	20	Emergency medicine	10
Engineering environmental	20	Medical informatics	9
Environmental sciences	19	Nuclear science technology	9
Oncology	19	Spectroscopy	9
Social sciences interdisciplinary	19	Gastroenterology hematology	8
Business	18	Planning development	8
Computer science hardware	18	Geochemistry geophysics	7
Geosciences multidisciplinary	18	Public environmental occupational health	7
Materials science characterization	18	Rehabilitation	7
Thermodynamics	18	Acoustics	6
Chemistry organic	15	Biology	6
Materials science coatings films	15	Crystallography	6
Physics fluids plasmas	15	Economics	6
Engineering aerospace	14	Ophthalmology	6
Engineering geological	14	Water resources	6

The most largest number of publications in 3D printing field is found to be in Material science. Publications in civil engineering and construction building technology on a global scale are found to be few in number when it is compared to other engineering fields. For example, the ratio of publications in civil engineering to publications in electrical and electronic engineering is 3.1%.

Publications related to 3D printing field in all disciplines on a global scale increase by years are represented in Figure 2.

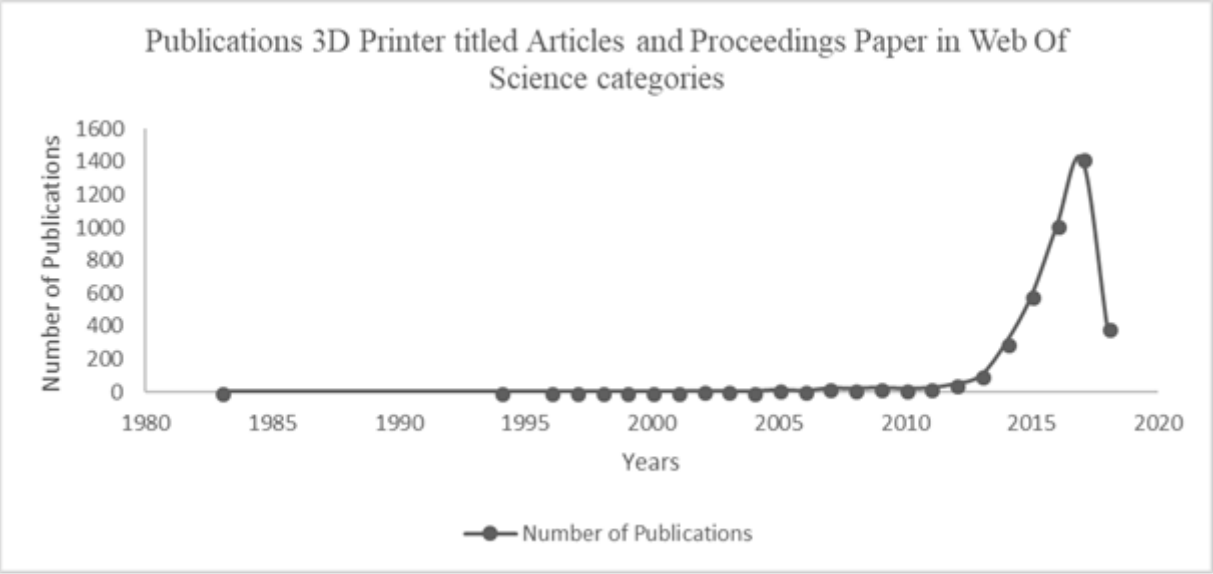

Figure 2. Publications 3D printing titled articles and proceeding papers in Web of Science database

Publications in civil engineering and construction building technology are evaluated and listed in Table 4 as follows: name of the publication, author name/s, year of the publication, place of the publication and subject of the study. In publications related to civil engineering, publications that experimentally tested the mechanical properties of concrete printed with a 3D printer are found. In publications related to civil engineering, the use of waste and recycable materials in cement waste for 3D concrete printing is focused and investigated. 3D printing for home or office construction, projects need to be created with the building information modeling process.

Table 4. Publications in civil engineering and construction building technology (Web of Science)

Title	**Authors/Year/ Location**	**Subject**
Mechanical properties of structures 3D printed with cementitious [4].	Peng Feng, Xinmiao Meng, Jian-Fei Chen, Lieping Ye. 2015. China	A study on mechanical behavior of 3D printed structures using cemented powder. Compression and flexural tests were performed to determine the mechanical properties and fault characteristics of these materials.
Digital reproduction of historical building ornamental components: From 3D scanning to 3D printing [7].	Jie Xu, Lieyun Ding, Peter E.D. Love. 2017. China	Using a combination of 3D scanner and 3D printing technology, a study was carried out by scanning an existing building element and re-modeling it by cement-based printing and examining the compressive strength of this reinforced concrete element.

Title	**Authors/Year/ Location**	**Subject**
Visualization of the 3D structure and stress field of aggregated concrete materials through 3D printing and frozen-stress techniques [8].	Yang Ju, Li Wang, Heping Xie, Guowei Ma, Lingtao Mao, Zemin Zheng, Jinbo Lu. 2017.China	3D printing models based on X-ray micro focal computed tomography (CT) imaging of a concrete sample were used to replicate the complex aggregate structure into a transparent matrix, by introducing a new approach to identifying 3D stress areas that are difficult for concrete materials.
Printable properties of cementitious material containing copper tailings for extrusion based 3D printing [5].	Guowei Ma, Zhijian Li, Li Wang. 2018. China	With recycled or waste materials for 3D concrete printing, it may be possible to obtain environmentally compliant and low cost printing. Experimental results of waste use were evaluated in the study.
Crushing behavior of a thin-walled circular tube with internal gradient grooves fabricated by SLM 3D printing [9].	Zhe Yanga, Yangyang Yub, Yanpeng Weia, Chenguang Huanga. 2017. China	Experimental mechanical behavior of a Steel Pipe produced by selective laser melting technique with 3D printer has been studied.
Classification of building systems for concrete 3D printing [10].	R. Duballet, O. Baverel, J. Dirrenberger. 2017. France	Specific parameters highlighted-scale, environment, support, and related assembly strategies - and introduced a classification method. Construction systems based on 3D printing processes have been characterized. Different approaches and then cartography of robotic complexity are proposed.
Penetration of cement pastes into sand packings during 3D printing: analytical and experimental study [11].	Alexandre Pierre, Daniel Weger, Arnaud Perrot, Dirk Lowke. 2018. France	The relationship between the pressure strength of the materials in 3D concrete printing with cement paste was studied.
Structural built-up of cement-based materials used for 3Dprinting extrusion techniques [12].	A. Perrot, D. Rangeard, A. Pierre. 2016. France	In the case of layer printing with 3D printer of cement-based materials, mechanical properties of the material in one layer and the effects of the next layer on this layer were studied.
Use of calcium sulfoaluminate cements for setting control of 3D – printing mortars [13].	Noura Khalil, Georges Aouad, Khadija El Cheikh, Remond S. 2017. France	Experimental mechanical properties of printable mixtures made of two different types of cement to control the printability of mortars for printing quality in 3D concrete printing were studied (only abstract).

Title	**Authors/Year/ Location**	**Subject**
Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete [14].	Babak Zareiyan, Behrokh Khoshnevis. 2017. United States	Using experimental approaches for 3D-print reinforced concrete structures, we examine the link between bond strengths of contoured building layers. A concrete mix compatible with the existing extrusion system was used and different locking connections were tested.
Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture [15].	Ali Kazemian, Xiao Yuan, Evan Cochran, Behrokh Khoshnevis. 2017. United States	In terms of shape stability, print quality and printable for 3D concrete materials, a laboratory testing process has been developed that applies to all 3D concrete materials.
3D documentation and printing in forensics [16].	Kevin A. Kianka. 2015. United States	A study that indicates that 3D imaging and document creation technologies can be used and useful in many forensic cases in building collapses (only abstract).
Performance of 3D computers and 3D printed models as a fundamental means for spatial engineering information visualization [17].	Gabriel B. Dadi, Timothy R.B. Taylor, Paul M. Goodrum, William F. Maloney. 2016. United States	A 2D drawing of a project and 3D drawing in computer environment, and model printing with 3D printer will be the right information management process for the final product to emerge.
3D printing for construction: a procedural and material-based approach [18]	A. Nadal, J. Pavón, O. Liébana. 2017. Spain	The 3D printer used in the construction industry is limited by the reason of material optimization and procedure because of the lack of cost and procedural guidelines required by technology. This study has developed methodology to prevent these limitations.
Material use optimization in 3D printing through a physical simulation algorithm [19].	Adolfo Nadal, Hugo Cifre, Juan Pavón, Óscar Liébana. 2017. Spain	Algorithms for pattern models have been developed for large 3D printing parts that are needed in the construction industry and the use of non-standardized customized nozzle designs, printing materials has been discussed for greater usability.
High-resolution model mesh and 3D printing of the Gaudí's Porta del Drac [20].	Juan Corso, Pilar Garcia-Almirall, Adria Marco. 2017. Spain	3D scanner and 3D printing technology and a study of the unique elements of architectural heritage. A case study has been examined within the scope of the study.

Title	**Authors/Year/ Location**	**Subject**
Effects of anisotropic voids on thermal properties of insulating media investigated using 3D printed samples [21].	Sang-Yeop Chung, Dietmar Stephan, Mohamed Abd Elrahman, Tong-Seok Han. 2016. Germany	Using a 3D printer to investigate the material influences of the insulating material created a series of insulating media with different anisotropic voids.
Properties of 3D-printed fiber-reinforced Portland cement paste [22].	Manuel Hambach, Dirk Volkmer. 2017. Germany	The behavior of Portland cement reinforced with short fibers in 3D printing conditions was experimentally investigated taking into consideration the order of fibers and the direction of printing.
3D-ETFE:Development and evaluation of a new printed and spatially transformed foil improving shading, light quality, thermal comfort and energy demand for membrane cushion structures [23].	Jan Cremers, Hannes Marx. 2017. Germany	A study on the development of ethylene-Tetra-fluoro-ethylene membranes with 3D printing method to gain better performance and mechanical properties.
Modified 3D printed powder to cement-based material and mechanical properties of cement scaffold used in 3D printing [24].	Pshtiwan Shakora, Jay Sanjayan, Ali Nazari, Shami Nejadi. 2017. Australia	In the 3D printed cubic samples taken with a unique cement mixture, the mechanical properties of the material were observed at different saturations, and the best cement dust detection study was performed.
Parametric customization of a 3D Concrete printed Pavilion [25].	Thomas Fischer, Christiane M. Herr. 2016. Australia	In the context of local Chinese construction, an overview of the research and development efforts for 3D concrete printing was presented (only abstract).
From research to practice: exploring 3D printing in production of architectural Mashrabiya [26].	Dustin Headley, Nehal Almerbati, Peter Ford. 2015. Australia	Offers robotic help with crafts that have been lost due to lack of skilled workers and suggestions on how to make mashrabiya with 3D printer (only abstract).
3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM [1].	Mehmet Sakin, Yusuf Caner Kiroglu. 2017. Turkey	The importance of BIM for the 3D printer and the current status of the 3D printer and the future were mentioned.

Title	**Authors/Year/ Location**	**Subject**
Design 3D printing cementitious materials via Fuller Thompson theory and Marson – Percy model [27].	Yiwei Weng, Mingyang Li, Ming Jen Tan, Shunzhi Q. 2018. Singapore	Fuller Thompson theory and Marson-Percy model were used for the design of cementitious materials for 3D Cementitious Materials Printing (3D CMP). Fuller Thompson theory and Marson-Percy model can be used as a reasonable guideline for designing material rheology for 3D CMP.
3D printing of reinforced concrete elements: Technology and design approach [28].	Domenico Asprone, Ferdinando Auricchio, Costantino Menna, Valentina Mercuri. 2018. Italy	The 3D concrete printing technology offers a new approach to the acquisition of a new solid construction material by integrating separately printed materials and steel elements
3D printing of buildings and building components as the future of sustainable construction? [29].	Izabela Hager, Anna Golonka, Roman Putanowicz. 2016. Poland	The benefits of 3D printing to architectural challenges and the pioneering work and the future location of the review were made.
Technology for Subsea 3D Printing Structures for Oil and Gas Production in Arctic Region [30].	H N Musipov, V S Nikitin, L N Bakanovskaya. 2017. Russia	With the help of 3D printers, it is a study that examines submarine oil and gas drilling unit construction technology. It is dealt with in the design of living spaces. Approximate economic efficiency calculation of the use of 3D printing technology is given.
Assessing surface DEM and roughness with a 3D Printed gravel bed [31].	S. Bertin, H. Friedrich, P. Delmas. 2016. New Zeland	The study, which shows that the reliability of digital elevation models is less in controlling the smoothness of gravel river beds, presents a realistic model according to the known heights with the 3D printing system on the roughening control and presents experimental studies on it. (only abstract)
Creating the fleet maker: 3D printing for the empowerment of Sailors [32].	Michel A. Audette, Vukica M. Jovanovic, Onur Bilgen. 2017. United States	Not relevant (only abstract).

Title	**Authors/Year/ Location**	**Subject**
Evaluation of Different Topologies of Integrated Capillaries in Effective Structural Health Monitoring System produced by 3D Printing [33].	Maria Strantza, Reza Vafadari, Dieter De Baere. 2015. Belgium	Not relevant (only abstract).
Real- time process Monitoring and Temperature Mapping of a 3D Polymer Printing Process [34].	Ralph B. Dinwiddie, Lonnie J. Love, John C. Rowe. 2016. United States	Not relevant (only abstract).
Airborne particle emission of a commercial 3D printer: the effect of filament material and printing temperature [35].	L. Stabile, M. Scungio, G. Buonanno, F. Arpino, G. Ficco. 2017. Italy	Not relevant.

There are 241 publications in the field of pubmed scanning, excluding "web of science" in the field of medicine, which contain "3D printer" and "medicine" words and/or title.

CONCLUSIONS

The increasing number of publications by years reveals that the 3D printing technology is becoming more and more popular in all industries. It is seen that the developed countries and the countries with high GNP focus on 3D printing technologies. The 3D printing technology is a part of industry 4.0 [36]. Therefore, it’s an undeniable fact that 3D printing field is a promising research area for growth in the construction industry. In order to solve Saudi Arabia's growing population and the demand for housing quickly and economically, the company (Al-Mobty Group) purchased a hundred 3D printers for residential printing, worth 1.5 billion US $ from China's Winsun by leasing in 2017. The fact that the sales contracts of 3D printers are also at the top reveals the progress that the private sector has achieved in the industry. These developments reveal the strategic positions that countries should take in terms of 3D printing [37]. It is predictable that applications in the private sector will improve. Furthermore, 3D printing technology is used by NASA, which wants to use the technology in the creation of extraterrestrial habitats. It is obvious that printing technologies need further developments and research. 3D printing technologies may improve the time and cost management in construction, lean construction, green approaches, and sustainability in construction industry. This finding indicates that studies in 3D printing technology field will be more valuable in the near future. From regional point of view, it is necessary to research the opportunities of 3D printing for construction industry in The Republic of Turkey, which targets to enter among the top 10 economically developed countries in the world. It is important for The Republic of Turkey to conduct academic studies in the area and raise number of experts in 3D printing. So that the industry can carry out integrated approach to new 3D printing technologies in order to achieve the future projections in the field. Like the

other industries, construction industry may benefit from 3D technology. Therefore future research intentions in construction will be under high affect of 3D printing technology field.

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