WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.155121

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 3 2025

pp. 601 –618

Research paper

3D concrete print – regional potential and challenges

Anna M. Stręk[1], Alena Sičáková[2]

Abstract: The article aims at identifying scientific and industrial development prospects in 3D concrete printing with focus on regional potential. The main research method consisted in a study of field literature enhanced by a bibliometric survey and analysis of means of intellectual property protection. For the bibliometric investigation there was collected detailed data about publications regarding concrete additive manufacturing. The gathered information included among others: year of publication, scope, authors with affiliations, citations, *etc*. The data was analysed in sets and subsets with the objective of identification of mutual relations and influence paths. Tag cloud creation and analysis was also performed as an auxiliary tool for the investigation. Additionally, a patent and intellectual property database referring to concrete printing was studied to provide some insight into industrial implementation and commercialisation potential. The results allowed for concluding which aspects seemed to be most significant for the development of the concrete printing science and application. Additionally, propositions of paths for further research and development were determined. The presented results could be a used as guidance reference for regional scientific and industrial partners.

Keywords: 3DCP, concrete printing, additive manufacturing

[1]DSc. Eng., Cracow University of Technology, Faculty of Civil Engineering, ul. Warszawska 24, 31-155 Krakow, Poland, e-mail: anna.strek@pk.edu.pl, ORCID: 0000-0001-6366-4857

[2]Prof., PhD., Eng., Technical University of Košice, Faculty of Civil Engineering, Vysokoškolská 4, 042 00 Košice, Slovakia, e-mail: alena.sicakova@tuke.sk, ORCID: 0000-0001-7351-502X

1. Introduction

Additive manufacturing (AM) can be referred to as "a new digital manufacturing technology that integrates machinery, computer, numerical control and materials in the field of global advanced manufacturing" [1]. According to [2], "AM has positioned itself as the backbone of Industry 4.0 for the manufacturing world" and is contributing to it along with other advanced technologies, like cloud computing, big data, artificial intelligence, internet of things, radio-frequency identification, robotics, etc. The official definition is given in the ISO/ASTM 52900 standard [3]: a "process of joining materials to make parts from 3D model data, usually layer upon layer". One of the industrial fields where AM has a significant impact is construction and architecture.

Application in construction is tied to technologies associated with typical building materials, of which, concrete can be considered a key one. An additive manufacturing process performed with concrete is often referred to as: 3D concrete printing (3DCP). Among a total of 15 AM methods for application in the construction industry presented by [4] in seven categories, the following are mentioned for concrete processing: Contour Crafting (CC) and Concrete Printing (CP) in the Extrusion category, and D-Shape (DS) and Three-Dimensional Printing (3DP) in the Binder Jetting category. Considering [5] as one of the first publications to suggest the use of AM in making large structures for the construction branch, the application of AM in the building industry is, according to [4], rather new and still in an early phase of advancement. However, "over the past decade, there has been a dramatic development in the research of extrusion-based 3D concrete printing" [6]. This is a promising prospective, since cities and other built environments facing housing shortage crisis search for solutions [7]. 3DCP could be one of the answers [8], along with or instead – depending on the needs – the already used methods like e.g. prefabrication [7]. But, there are yet no standards or officially approved design codes and printers and mixtures are not widespread commercially available. According to [9, 10], 3DCP is gradually developing towards stable and standardised production processes in aspects such as mixtures and robotic printers. However, other aspects, like for example digital 3D modelling tools, do not advance at the same pace and are not fabrication-aware [9, 11].

Complexity of the issue as well as expectations of benefits of 3DCP technologies find response in research activities all over the world. Goals and specific foci of the research cover a broad variety of aspects: starting with theoretical works on possible applications and limits of technologies, through design solutions for printing mechanisms, solutions for composition of concrete mixtures, including also application of secondary raw materials, investigations of properties of mixtures for 3D printing, investigations of properties of construction elements manufactured by 3D printing (like sandwich beams) and so on [12–14]. The amount of information presented in the form of scientific articles is enormous and it is difficult to keep track of it. Also, progress in the discussed field of research as well as the degree of transfer of knowledge to the practice sphere varies among different regions of the world and depends on a number of aspects, such as: degree of international cooperation, support in research funding, engagement of industrial partners, etc.

Therefore, **the general aim of the investigation presented in this article** was to identify, using selected indicators, aspects of 3DCP that are the most advanced and subsequently possible gaps and to connect the findings to regional development potential with highlight on Central

Europe (CE) and especially the Visegrad Group (VG). For this purpose, a detailed bibliometric survey was performed (Sec. 2) and, additionally, means of intellectual property protection were studied (Sec. 3). Among **the main contributions of the presented work** one can count:

- data analysis with comparison of results in line: world – Central Europe – the Visegrad Group countries,
- identification of both strongly and poorly developed scientific and industrial aspects,
- propositions of directions potentially leading to the enhancement of the role of the Visegrad Group region in the 3DCP field.

2. Bibliometric research regardinG 3DCP

This chapter is divided into parts in accordance with the assumed structure of the research. Methods and tools used in the bibliometric survey are described in Subsec. 2.1. Next, Subsec. 2.2 gives an overall image of the state of the art of the 3DCP field in the world. Finally, Subsec. 2.3 is focused on a detailed analysis for Central Europe and the Visegrad Group.

2.1. Methods

Bibliometric analysis is an investigation tool basing on quantitative and qualitative study of extensive bibliographic data. Its first use is reported to be [15] and from that time it has gradually earned interest of institutions and individual researchers [16], as it allows for determination whether a considered topic is worth of scientific study and financial support [17].

In the presented research, two pieces of bibliometric software were used: the Web of Science (WoS) search engine with the Analysis and Citation tool [18] and the programme VOSviewer [19]. Additionally, the MS Excel software was also applied in the study.

Data for the bibliometric analysis was gathered with the use of the WoS search engine [18] from the WoS Core Collection database. This database was chosen, as it is a highly-regarded and reliable scientific citation indexing service [20]. The search comprised query for an alternative combination of the following four phrases: “3dcp” or “concrete print*” or “print* concrete” or “additiv* manuf* concrete”. The asterisks could be replaced by any chain of signs. Obtained results were then refined by elimination of irrelevant records. The final repository comprised 917 records, consisting of: 827 articles (including 96 review articles), 84 proceedings papers, 4 editorial materials and 2 news items. All found records were from the period: 2011–2023. However, since the research was performed in November 2023, one should take into account that the data for this year is not fully representative for the whole year period.

Even though WoS is a well-regarded and valuable database, it does not cover all published material and some of the only locally important journals might not be comprised in it. Similarly, patents, industrial press materials or other information also might not be included in it. Additionally, like in all databases, some incomplete or erroneous records might occur [21]. So the shown results of the bibliometric survey have to be considered with this reservation in mind.

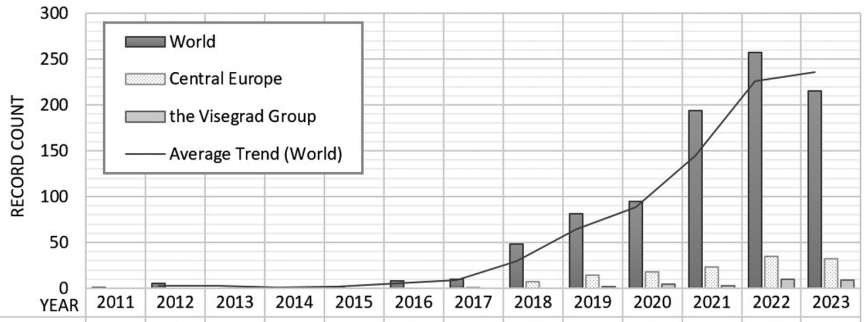
A set of indicators was assumed in the analysis to facilitate identification of trends, relations and formulation of conclusions. The following factors were chosen for finding the global image

for the 3DCP branch: number of publications in consecutive years, share of individual countries in authorship and keywords indicated in publications. On the other hand, the indicators selected in the analysis focused on CE and VG were in sequence: number of records in consecutive years, share of individual countries in authorship, analysis of citations (count of citing works, count of open-source publications, average citation count per item, Hirsch index, characteristics of citing items), co-authorship of records, funding by a given institution, institutional type share and, finally, a textual analysis of titles and abstracts of publications.

The focus of the presented study was especially on the Central Europe (CE) countries. Depending on the assumed classification criteria, different countries could be regarded as being part of the CE region. So, in this research it was chosen to take into consideration countries referred to in the EU Programme "Interreg Central Europe" [22], i.e.: Austria (AT), Croatia (HR), Czech Republic (CZ), Hungary (HU), Poland (PL), Slovakia (SK), Slovenia (SI), Germany (DE), Italy (IT). Also, a smaller subset was created for the countries of the Visegrad Group (VG): Czech Republic, Hungary, Poland, Slovakia.

2.2. Results for the global overview

In this subsection, there are presented results of the bibliometric survey for identification of trends in the global 3DCP field. The first analysed factor was the **number of records in consecutive years** (Fig. 1). The research confirmed that the topic of 3D concrete printing is a relatively new and promisingly developing field: the first record in the database is from 2011 and a significant rise of interest started in the world literature from 2018 and has continued until today (the trend line).



YEAR	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
World	1	5	0	1	2	8	10	48	81	95	194	257	215
Central Europe							1	7	14	18	23	35	32
the Visegrad Group									2	4	3	10	9

Fig. 1. Number of records per year

Regarding the **share of individual countries in authorship**, results are depicted in Fig. 2. Attribution of an article to a given country count was based on the location of authors' affiliated institutions. If for a given work there were authors representing institutions from more than one country, the article was attributed once to the count for all mentioned counties. Thus, since some works have authors from more than one country, the total count in the graph sums up to

1318 and not to 917. Also, 7 records did not contain data in the analysed field (compare: [21]). The biggest share belongs to People's Republic of China (CN): 275 authored or co-authored records, which is 30.0% of 917 database records. Next are Australia (AU) with 119 records (13.0%) and the United States of America (US, USA) with 103 (11.2%).

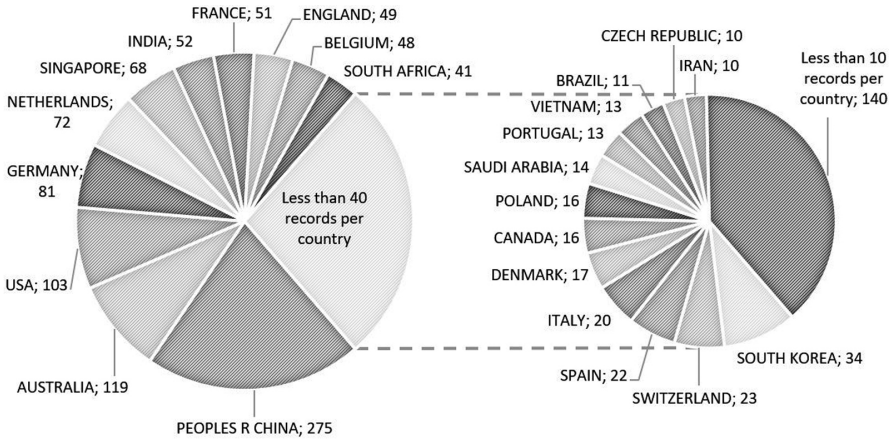


Fig. 2. Country share in authors' affiliations; the right circle is a detailed development of the part "Less than 40 records per country" visible in the left circle

There was also made an **analysis of keywords**, basing on their co-occurrence. Table 1 gives 20 most frequently used keywords with their occurrence percentage. One can observe that some keywords repeat in variant forms (e.g. 3d concrete printing, 3d printing, 3d printed concrete). Also, some are too general (design, behavior). The lowest percentage in Table 1 (7.9%) is

Table 1. Twenty most frequently used keywords together with their occurrence percentage

Keyword (1–10)	**Occurrence percentage**	**Keyword (11–20)**	**Occurrence percentage**
3d concrete printing	34.2%	behavior	15.7%
construction	27.8%	mechanical-properties	14.3%
performance	24.1%	rheology	13.6%
strength	21.8%	3d printed concrete	10.3%
concrete	20.9%	fresh properties	10.3%
design	18.3%	geopolymer	10.3%
extrusion	18.1%	digital fabrication	9.5%
hardened properties	17.8%	fresh	8.8%
3d printing	16.2%	cementitious materials	8.6%
additive manufacturing	16.0%	thixotropy	7.9%

correlated to a given keyword appearing in 72 out of 917 database items. In order to identify more specific terms, a keyword cloud was generated with the main assumption that a given term should occur in at least 9 items in the database (~1% of records). It is presented in Fig. 3.

The graph in Fig. 3 shows that a considerable part of works is devoted to deformation and time-dependent behaviour: rheology, viscosity, flow, thixotropy, e.g. [23–25]. Quite many keywords are associated with evaluation of mechanical properties, like yield stress, compressive or flexural strength, e.g. [26, 27]. Another broadly investigated topic is the interface between the printed layers: interlayer adhesion, interlayer bond strength, e.g. [28–30]. There are also fabrication aspects found among the researched areas: extrudability, ductility, e.g. [30–32]. Some account is attributed also to reinforcement in 3DCP, e.g. [33–35]. Further, many items in the database refer to mixture design and additions: fly ash, geopolymer, e.g. [36–38]. Finally, environmental aspects are also raised: sustainability, life cycle assessment, e.g. [39–41].

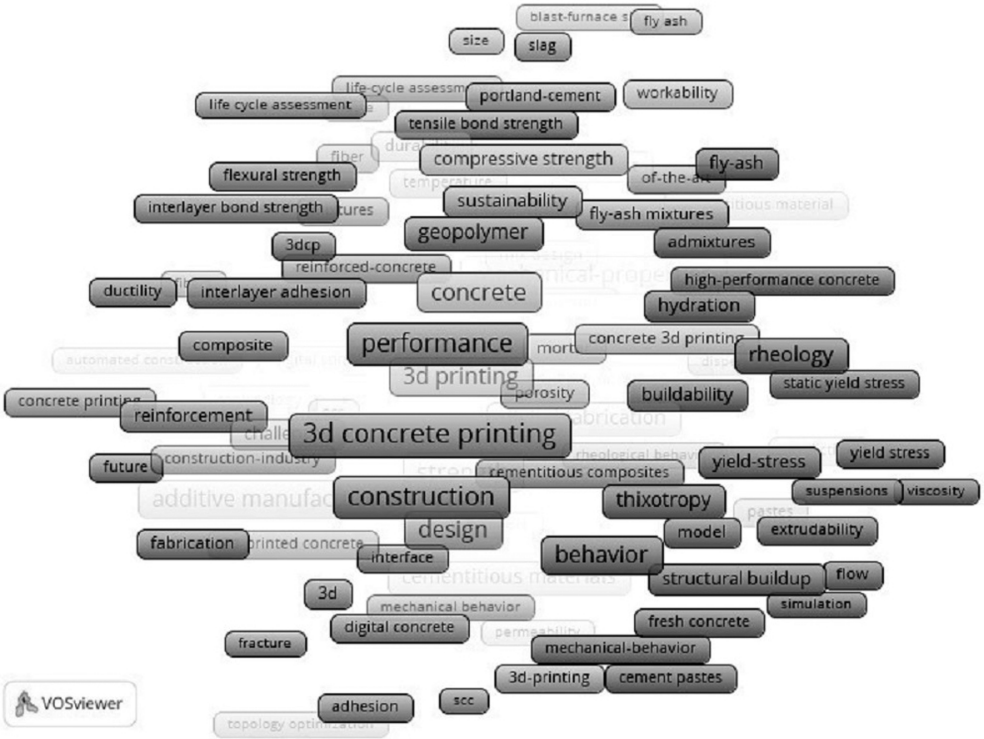


Fig. 3. The cloud of keywords occurring in at least ~1% of records

2.3. Results of the analysis with highlight on CE and VG

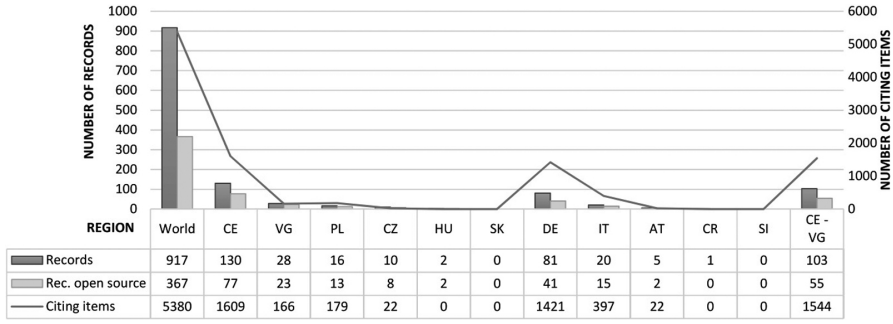
This subsection is devoted to a detailed bibliometric analysis with focus on Central Europe and especially the Visegrad Group. Results for the selected indicators, which were listed in the penultimate paragraph of Subsec. 2.1, are now going to be presented and discussed in sequence.

Looking back at Fig. 1, it can be observed that, regarding the **number of records in consecutive years**, data for CE and VG are in agreement with the global trend. However, some delay is visible: the first publication years were 2017 and 2019, for CE and VG respectively, and the count growths started in 2019 and 2022, also respectively.

Considering the **share of individual countries in authorship**, the first country from the CE set to appear in the graph in Fig. 2 is Germany – just outside the podium with 81 records, which is 8,8% of all items. All other countries of Central Europe have a considerably smaller number of items in the database: Italy – 20 records (2.2%), Poland – 16 records (2.2%), Czech Republic – 10 records (1.1%), Austria – 5 records (0.5%), Hungary – 2 records (0.2%), Croatia – 1 record (0.1%). Slovakia and Slovenia are not associated with any of the database records. The total Central Europe's share is 130 records (14.2% of 917) and the Visegrad Group is associated with 28 items (3.1%).

In terms of the assessment of impact of works elaborated in CE, VG and their countries individually, an **analysis of citations** was performed. The citing items database included auto-citations.

Figure 4 presents count of items per region (left axis) and **count of works citing** these items (right axis). These results are accompanied by Fig. 5 which shows how the share of **open-source publications** (left axis) is reflected with two citation measures: **average citation count per item** and **Hirsch index** (H-index), (right axis). The highest citing items count of the



REGION	World	CE	VG	PL	CZ	HU	SK	DE	IT	AT	CR	SI	CE - VG
Records	917	130	28	16	10	2	0	81	20	5	1	0	103
Rec. open source	367	77	23	13	8	2	0	41	15	2	0	0	55
Citing items	5380	1609	166	179	22	0	0	1421	397	22	0	0	1544

Fig. 4. Number of citations with respect to region

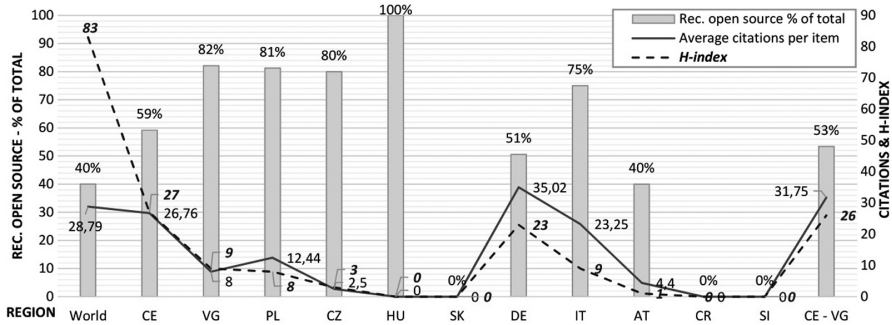


Fig. 5. Citation measures with regard to open source percentage

CE states belongs to Germany – works associated with this country were cited in 1421 items. Germany has also the highest average citation count per item: 35.02, exceeding the result for all countries indexed in the whole database: 28.79. Interestingly, the percentage of open source publications is not distinctly correlated with citation results.

The **characteristics of citing items** was analysed in terms of which countries use the works of CE and VG the most (Table 2). The first four countries in terms the of authorship of records (compare: Fig. 2) were also the first four regarding citing works elaborated in CE and almost the first for works from VG. In VG, the most citing country was Poland. These results seem to prove that CE and VG are significant and influential in research and development 3DCP.

Table 2. Top ten countries citing works associated with CE (left) and VG (right)

Country	Record count	Country	Record count
Peoples R. China	505	Poland	43
United States of America	193	Peoples R. China	36
Germany	186	United States of America	16
Australia	138	Germany	15
England	91	Australia	10
France	84	India	10
India	83	Czech Republic	9
Belgium	76	Belgium	8
Netherlands	74	England	8
Switzerland	69	South Korea	8

Another studied indicator was the **co-authorship of records**. Fig. 6 depicts a graph in which countries of CE are shown together with links representing co-authorship, both mutual as well as to countries from outside CE. The thicker the link, the more co-authored items. Interestingly, the world's top three players in the field of 3DCP (compare Fig. 2), namely: CN, AU and US, are not dominant among the partners of the CE countries. Of the three, China has the biggest share of co-authorship, Australia and the USA have comparable shares. They are related to Germany, Italy and Hungary.

Of the CE countries the most dense and strong network of links is associated with Germany, then Italy and Poland. Germany is connected to many European countries, the strongest links are with the Netherlands and Belgium. It also has a distinct link with China and light with the USA and Australia. Also, they have a few other overseas partners. As for Italy, most of its collaborators are from Europe, with the strongest link to Switzerland. Partners from outside the continent include the world's three leaders (with the strongest link to CN) and a few other countries. Poland, however, has a different cooperation pattern compared with the other two regional leaders. It collaborates slightly more with states from outside Europe (4) than within the continent (3) and is not linked to any of the world top three publishing countries. Regarding the remaining members of CE, the international cooperation is not as

distinct. Austria has 4 European collaborations and 1 with Mid-East. Hungary co-authors with 2 states. Czech Republic is associated only with Finland. And finally, Croatia has no links to other countries.

Regarding the internal cooperation within CE, it can be seen in Fig. 6 that it is not developed to a significant extent. There are only individual examples of co-authored items (links between Austria-Germany, Italy-Germany, Poland-Germany). Within VG there was no mutual collaboration indicated.

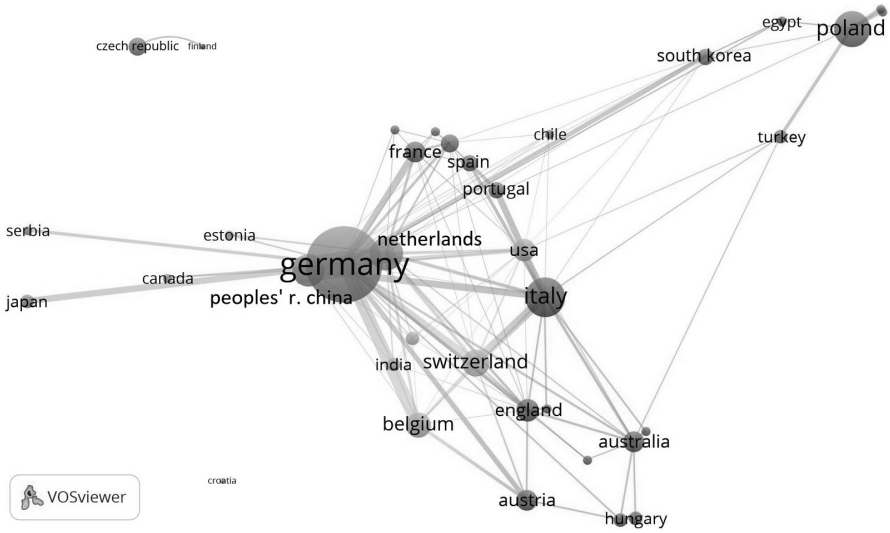


Fig. 6. Co-authorship of records from the CE set

As for the next analysed indicator, namely **funding by a given institution**, Table 3 shows relevant results. The table gives information about how many records in the CE subset of the database indicated the given sponsoring unit. There was no information about money quota, and also 42 records from the CE subset of the database and 8 records from VG subset did not contain suitable data to include in the founding statistics. There were 83 different sponsoring units identified in total, majority of them were associated with single records. So, for the sake of data presentation clarity, it was decided to present the names of institutions only for the top five record counts of the CE subset and additionally all remaining identified European Union organs or funding programmes (below the double line). Interestingly, founding of research associated with VG is separate from the support of the remaining CE states. This confirms low cooperation level within the region, which was already mentioned in the previous paragraph.

Database records were also analysed in terms of **institutional type share**, Fig. 7. Results show that academic units are dominant; such affiliations were found for 103 out of 130 works associated with the CE and for 24 out of 28 associated with VG. Research institutes also have a considerable share: 18 affiliations for CE and 4 for VG. Commercial partners co-authored 22 items from the CE database subset and 3 from the VG one. State agencies, societies and army were affiliated to single records.

Table 3. Institutions providing funding for research and/or publication of database items associated with the CE and VG countries (top five record count results + EU funding)

Funding Agencies	Record Count
German Research Foundation DFG	29
National Natural Science Foundation of China (NSFC)	9
Swiss National Science Foundation (SNSF)	6
National Key Research and Developement Program of China	6
European Structural and Investment Funds of the Operational Programme Research Development And Education	5 (all VG)
Federal Ministry of Education Research (BMBF)	3
National Centre for Research and Development in Poland	3 (all VG)
Innovation Fund Denmark	3
Ministry Of Education and Science (Poland)	3 (all VG)
Technology Agency of Czech Republic	3 (all VG)
Gerhard and Karin Matthai Foundation	3
Technische Universitaet Braunschweig	3
European Regional Development Fund	2
European Research Council (ERC)	1
European Social Fund on Research and Innovation	1
H2020 Societal Challenges Programme	1

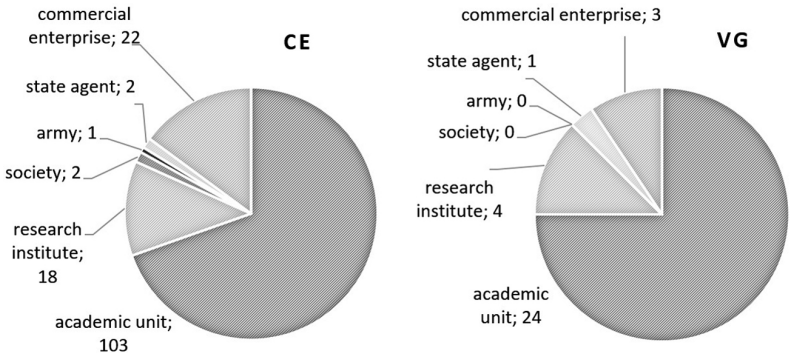


Fig. 7. Types of affiliated units: CE (left) and VG (right)

In order to identify specific research fields which are explored in the CE associated records, **a textual analysis** with VOSviewer [19] was performed. Please note that in contrast to analysis of keywords, which are usually determined and provided by authors (compare: the keyword analysis in Subsec. 2.2), here, the investigated text comprised titles and abstracts from the

database records and based on natural language processing algorithms [42]. The textual analysis was chosen over the keyword analysis in case of the CE record subset for the following two reasons: first, there were considerably less records in the CE subset than in the whole database; and second, textual analysis of natural language is more flexible and provides less general terms, allowing for a more detailed insight into specific research areas.

At the beginning of the analysis, the software algorithmically retrieved a list of 3551 terms from the record database using the following major assumptions: only English language, occurrence in at least one database record, disregard relevance coefficient automatically attributed by the software, disregard number of occurrences in a single record. Next, the phrase list was meticulously elaborated: irrelevant entries were deleted, also too general or too specific terms were eliminated and variants with the same or very close meaning were rephrased so as to be expressed in a cohesive way. The final version of the term list comprised 230 entries. Table 4 shows twenty most frequently used phrases together with their occurrence percentage. The lowest shown percentage 12.3% corresponds to a given phrase appearing in 16 out of 130 record items associated with CE. Fig. 8 shows the term cloud of phrases occurring in at least 7 database records (i.e. in at least ~5% of records); allowing to notice minor, but still significant research areas. Also, in this case co-occurrence links are provided in the figure.

Table 4. Twenty most frequently used phrases together with their occurrence percentage

Phrase (1–10)	**Occurrence percentage**	**Phrase (11–20)**	**Occurrence percentage**
experiment	52,3%	mechanical behaviour	15,4%
layer	48,5%	mortar	15,4%
extrusion	30,0%	strength	15,4%
reinforcement	23,1%	mixture	13,8%
model	23,1%	compressive strength	13,1%
cement	20,0%	environment	13,1%
time	19,2%	numerical analysis	13,1%
addition	19,2%	solution	13,1%
mechanical property	17,7%	deformation	12,3%
composite	16,9%	geometry	12,3%

One can see that most of the identified phrases refer to similar research areas that were identified in the keyword analysis of the whole record database (Subsec. 2.2); but even though, some aspects are noticeably more pronounced. Firstly, vast majority of works refer distinctly to some experimental procedure. On the other hand, however, the field of theoretical and computational analysis is marked by terms like: constitutive modelling, finite element method, numerical analysis, simulation (e.g. [43–45]). Also, some works are connected with printers construction, which is implied by phrases like: robotic arm, automation (e.g. [46, 47]).

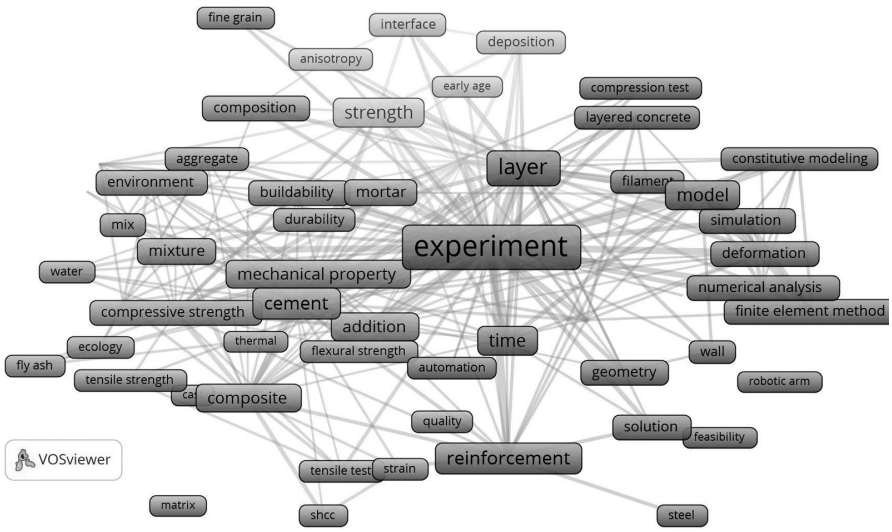


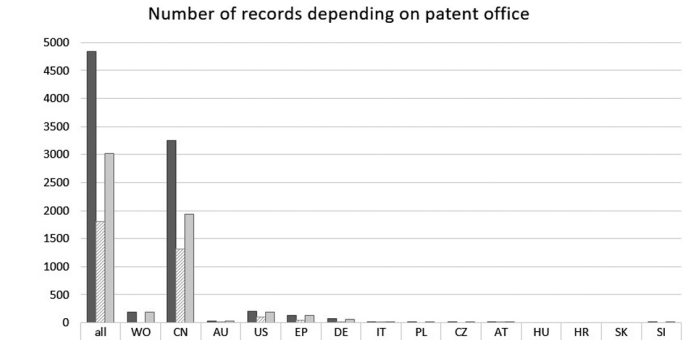
Fig. 8. The term cloud for phrases occurring in at least 7 CE associated records

3. Patents and related intellectual property protection solutions

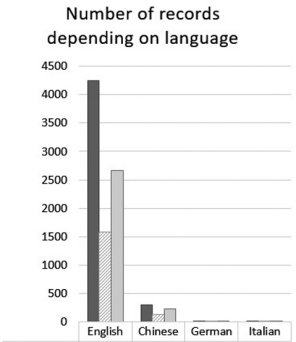
By its very nature, the bibliographic analysis performed on records from Web of Science Core Collection gave results oriented more towards science and research than commercialisation and economy. Some insight into the industrial side of the 3DCP technology can be obtained by investigation of patents and related forms of intellectual property protection, like for example utility patterns. Such a study was conveyed with the use of the Google Patents search engine [48]. The searched phrase comprised a Boolean alternative of combinations of the terms: "concrete", "mortar", "cement", "cementitious" with the terms: "print", "printed", "printing". The acronym "3DCP" was also included in search. There was assumed a limiting condition that records must be from the period: 1990–today.

In result a database of 4837 records was retrieved. The records were then analysed in terms of **status of protective documents** (granted *vs* application) and **patent offices in which documents were filed**. Into consideration there were taken patent offices in the 9 countries of CE, patent offices in the 3 countries leading in the publications number (see: Subsec. 2.2, Fig. 2) and patent offices for European and world protection. Also, **language of documents** was analysed.

The survey results are shown in Fig. 9, acronyms of patent offices referring to specific countries and regions are consistent with symbols assumed earlier in the test and the symbols assumed by the European Patent Office [49]. Please note, that some documents might have been filed at multiple patent offices and while the same document could have already acquired the granted status in one office it might have the application status in another, so the granted and application status numbers cannot be summed up to total. Also, a patent office to which



	all	WO	CN	AU	US	EP	DE	IT	PL	CZ	AT	HU	HR	SK	SI
All records	4837	190	3254	29	203	130	67	3	4	3	6	0	0	0	1
Grant	1813	0	1320	6	100	42	20	1	0	0	3	0	0	0	0
Application	3024	190	1934	26	182	125	54	3	4	3	5	0	0	0	1



	English	Chinese	German	Italian
All records	4237	309	22	3
Grant	1578	136	8	1
Application	2659	232	19	3

Fig. 9. Intellectual property records number with respect to patent offices (left) and language (right)

a document was filed does not straightforward represent the region or country of affiliation of the author of the document or the inventor, since one author can file applications in many offices. These remarks should be taken into consideration in interpretation of results in Fig. 9.

The overwhelming majority of records was filed at the patent office in China: 3254, which is 67.3% of all records. Following are the offices: US with 203 records (4.2% of all), WO with 190 records (3.9%) and EP with 130 records (2.7% of all). As for the patent offices in the countries of CE, Germany has the biggest share – 67 records, which is 1.4% of all. Patent offices in Austria, Poland, Italy, Czech Republic and Slovenia were associated each with $\leqslant$ 6 records (each $\leqslant$ 0.12% of all). Hungary, Croatia and Slovakia's offices were not associated with any documents in the database. As for the languages of documents collected in the database, a full analysis was not possible, since the Google Patent search engine provided record count only for part of the languages of the countries and regions considered in this study: English, Chinese, German and Italian. Nevertheless, even this narrowed range provided results giving insight into general proportions. Out of total 4571 records indexed in 4 chosen languages, 4237 were in English (92.7%). Chinese was the language of 309 documents (6.8%), German – 22 (0.5%) and Italian – 3 (0.1%).

Analysis of the intellectual property database agrees with the bibliography study: 3DCP is a quickly and widely developing branch with considerable application and commercialisation potential. Also, the same countries were identified as global and regional leaders.

4. Discussion and conclusions

The article has been designed to specify aspects that appear to be significant for the development of the concrete printing science and application, with focus on the potential of the Central Europe region and especially the Visegrad Group.

With regard to identification of both strongly and poorly developed scientific and industrial fields and aspects, basing on the conveyed analyses, we can present the following conclusions:

– To determine **current research areas in the CE countries**, the highest occurrence of words appearing in titles and abstracts was taken as a measure. In this way, the following general aspects of research can be identified: experimental studies, composition and properties of mixtures, reinforcement of structures, simulation and modelling. When compared to the keyword analysis from articles on a world scale, the analysis of titles and abstracts from the CE countries does not contain as many specific words related to the properties of fresh mixtures, like rheology, viscosity, extrudability. Interlayer aspects, like bond strength or adhesion, are also not often mentioned. On the other hand, more noticeably pronounced are: the field of theoretical and computational analysis (simulation, finite element method) and aspects of printers' construction (robotic arm).
– Both from the global as well as regional points of view there can be identified also **under-researched or poorly developed fields**. Among barriers in 3DCP one can count: lack of standards and codes for design and production (e.g. ISO or EC) and not widespread commercial availability of printers and mixtures. Solutions to overcome these impediments may be found by research and implementation collaborative projects, as well as industrial know-how development and trade protection.

Concerning propositions of directions potentially leading to the enhancement of the role of the VG region in the 3DCP field, the following conclusions can be drawn from the research:

– More **intellectual property protection** measures should be taken by the VG countries. Commercialisation potential is strictly linked to patents and know-how protection. The research showed that, that patent offices of Poland and Czech Republic were associated each with only $\leqslant 0.12\%$ of all patent database records, and Hungary and Slovakia's offices were not associated with any documents in the patent database. The biggest share of CE countries had the patent office of Germany 1.4% of all. In contrast, most records at a world scale were filed at the patent office of China: 67.3% of all records.
– **Improving collaboration from a regional point of view**. According to the survey results, China, Australia and USA, the world's three leaders in concrete printing, are not domineering co-authorship of the CE and VG countries. Cooperation of the CE states is considerably dispersed among partners all over the world. However, collaboration among the Central European partners is very weak (only single instances) and within VG there was no co-authorship indicated.
– **Improving collaboration from an institutional point of view**. To achieve the level of Industry 4.0, it is desirable to integrate research and development activities of academic, industrial and economical partners through relevant tools. According to the survey results, now academic units are found to be dominant among authors' affiliations: 103 out of 130 works (79%) associated with CE and 24 out of 28 (86%) associated with VG.

Both aspects of collaboration can be improved by using available funding schemes. Currently, the **Quadruple Helix** as a network type of relationships is preferred, including industry, government, academia and users/civil society. Among available funding schemes, the following two focusing on regional development can be mentioned here as exemplary solutions:

– **Visegrad fund**, as one reads on the fund's website [50], is "seeking advance innovative ideas addressing shared challenges by high quality regional cooperation projects. (. . .)

Organizations that aim to share knowledge, enhance innovation and engage citizens in the Visegrad region and across Central and Eastern Europe" are invited.

– **Interreg**, which, as the programme website [51] states, is "a key EU instrument that strengthens cooperation between regions and countries within the EU. Interreg plays a vital role in promoting regional development and cohesion. For the 2021–2027 period, Interreg is focused on addressing current challenges like climate change, digital transformation, and social inclusion.".

Acknowledgements

The present work was prepared within the frameworks of a scientific internship and authors would like to thank the Technical University of Kosice (TUKE) and Cracow University of Technology (CUT) for their support. Also, the article was partially prepared within the frameworks of the project of Slovak Scientific Grant Agency VEGA (Grant No. 1/0336/22) "Research on the effects of Lean Production / Lean Construction for improving the efficiency of on-site and off-site construction technologies".

References

[1] Y. Shi, Ch. Yan, Y. Zhou, J. Wu, Y. Wang, S. Yu, and Y. Chen, "Overview of additive manufacturing technology and materials", in *Materials for Additive Manufacturing. 3D Printing Technology Series*. Elsevier Ltd., 2021, pp. 1–8, doi: 10.1016/B978-0-12-819302-0.00001-8.

[2] R. Modupe Mahamood, T.C. Jen, S.A. Akinlabi, S. Hassan, K.O. Abdulrahman, and E.T. Akinlabi, "Role of additive manufacturing in the era of Industry 4.0", in *Woodhead Publishing Reviews: Mechanical Engineering Series, Additive Manufacturing*, M. Manjaiah, K. Raghavendra, N. Balashanmugam, J. Paulo Davim, Eds. Woodhead Publishing, 2021, pp. 107–126, doi: 10.1016/B978-0-12-822056-6.00003-5.

[3] ISO/ASTM 52900:2021(E) Additive manufacturing – General principles – Fundamentals and vocabulary. ISO/ASTM International, 2021.

[4] R. van Woensel, T. van Oirschot, M. Burgmans, M. Mohammadi, and K. Hermans, "Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry", *The International Journal of the Constructed Environment*, vol. 9, no. 1, 2018, doi: 10.18848/2154-8587/CGP/v09i01/57-81.

[5] J. Pegna, "Exploratory investigation of solid freeform construction", *Automation in Construction*, vol. 5, no. 5, pp. 427–437, 1997, doi: 10.1016/S0926-5805(96)00166-5.

[6] Y. Chen, S. He, Y. Gan, O. Çopuroğlu, F. Veer, and E. Schlangen, "A review of printing strategies, sustainable cementitious materials and characterization methods in the context of extrusion-based 3D concrete printing", *Journal of Building Engineering*, vol. 45, 2022, doi: 10.1016/j.jobe.2021.103599.

[7] A. Tofiluk, "Problems and challenges of the built environment and the potential of prefabricated architecture", *Archives of Civil Engineering*, vol. 69, no. 3, pp. 405–424, 2023, doi: 10.24425/ace.2023.146088.

[8] "A milestone for 3D concrete printing. 3D printed house". [Online]. Available: https://mense-korte.de/en/3d-printed-house. [Accessed: 24. May. 2024].

[9] L. Breseghello and R. Naboni, "Toolpath-based design for 3D concrete printing of carbon-efficient architectural structures", *Additive Manufacturing*, vol. 56, 2022, doi: 10.1016/j.addma.2022.102872.

[10] M.K. Mohan, A.V. Rahul, G. De Schutter, and K.V. Tittelboom, "Extrusion-based concrete 3D printing from a material perspective: A state-of-the-art review ", *Cement and Concrete Composites*, vol. 115, 2021, doi: 10.1016/j.cemconcomp.2020.103855.

[11] S. Bhooshan, T. Van Mele, Pand . Block, "Morph & Slerp: Shape description for 3D printing of concrete", in *Proceedings of the 5th Annual ACM Symposium on Computational Fabrication (SCF '20)*. New York: Association for Computing Machinery, 2020, pp. 1–10, doi: 10.1145/3424630.3425413.

[12] R.A. Buswell, W.R. Leal de Silva, S.Z. Jones, and J. Dirrenberger, "3D printing using concrete extrusion: A roadmap for research", *Cement and Concrete Research*, vol. 112, pp. 37–49, 2018, doi: 10.1016/j.cemconres.2018.05.006.

[13] G. Ma, R. Buswell, W.R. Leal da Silva, L. Wang, J. Xu, and S.Z. Jones, "Technology readiness: A global snapshot of 3D concrete printing and the frontiers for development", *Cement and Concrete Research*, vol. 156, 2022, doi: 10.1016/j.cemconres.2022.106774.

[14] M. Wesolowski, M. Ruchwa, and S. Rucevskis, "Nonlinear static analysis of truss core sandwich beams in three-point bending test", *Archives of Civil Engineering*, vol. 69, no. 4, pp. 459–475, 2023, doi: 10.24425/ace.2023.147670.

[15] A. Pritchard, "Statistical bibliography or bibliometrics?", *Journal of Documentation*, vol. 25, no. 4, pp. 348–349, 1969.

[16] O. Ellegaard and J.A. Wallin, "The bibliometric analysis of scholarly production: How great is the impact?", *Scientometrics*, vol. 105, pp. 1809–1831, 2015, doi: 10.1007/s11192-015-1645-z.

[17] O. José de Oliveira, F. Francisco da Silva, F. Juliani, L. César Ferreira Motta Barbosa, and T. Vieira Nunhes, "Bibliometric Method for Mapping the State-of-the-Art and Identifying Research Gaps and Trends in Literature: An Essential Instrument to Support the Development of Scientific Projects", in *Scientometrics Recent Advances*, S. Kunosic and E. Zerem, Eds. IntechOpen, 2019, doi: 10.5772/intechopen.85856.

[18] "Advanced Search Query Builder". [Online]. Available: https://www.webofscience.com/wos/woscc/advanced-search. [Accessed: 13. Nov. 2023].

[19] N.J. van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping", *Scientometrics*, vol. 84, pp. 523–538, 2010, doi: 10.1007/s11192-009-0146-3.

[20] C. Birkle, D.A. Pendlebury, J. Schnell, and J. Adams, "Web of Science as a data source for research on scientific and scholarly activity", *Quantitative Science Studies*, vol. 1, no. 1, pp. 363–376, 2020, doi: 10.1162/qss_a_00018.

[21] A. Maddi and L. Baudoin, "The quality of the web of science data: a longitudinal study on the completeness of authors-addresses links", *Scientometrics*, vol. 127, pp. 6279–6292, 2022, doi: 10.1007/s11192-022-04525-0.

[22] "Interreg Central Europe". [Online]. Available: https://interreg.eu/programme/interreg-central-europe/. [Accessed: 10. Nov. 2023].

[23] N. Roussel, "Rheological requirements for printable concretes", *Cement and Concrete Research*, vol. 112, pp. 76–85, 2018, doi: 10.1016/j.cemconres.2018.04.005.

[24] Y. Zhang, Y. Zhang, W. She, L. Yang, G. Liu, and Y. Yang, "Rheological and harden properties of the high-thixotropy 3D printing concrete", *Construction and Building Materials*, vol. 201, pp. 278–285, 2019, doi: 10.1016/j.conbuildmat.2018.12.061.

[25] J.J. Sokołowska, P. Woyciechowski, and M. Kalinowski, "Rheological Properties of Lunar Mortars", *Applied Sciences*, vol. 11, no. 15, art. no. 6961, 2021, doi: 10.3390/app11156961.

[26] A.V. Rahul, M. Santhanam, H. Meena, and Z. Ghani, "Mechanical characterization of 3D printable concrete", *Construction and Building Materials*, vol. 227, 2019, doi: 10.1016/j.conbuildmat.2019.116710.

[27] P. Feng, X. Meng, J.-F. Chen, and L. Ye, "Mechanical properties of structures 3D printed with cementitious powders", *Construction and Building Materials*, vol. 93, pp. 486–497, 2015, doi: 10.1016/j.conbuildmat.2015.05.132.

[28] A.J. Babafemi, J.T. Kolawole, M.J. Miah, S.C. Paul, and B. Panda, "A Concise Review on Interlayer Bond Strength in 3D Concrete Printing", *Sustainability*, vol. 13, no. 13, art. no. 7137, 2021, doi: 10.3390/su13137137.

[29] R. Napolitano, D. Forni, C. Menna, D. Asprone, and E. Cadoni, "Dynamic characterization of the layer-interface properties of 3D-printed concrete elements", *Case Studies in Construction Materials*, vol. 15, 2021, doi: 10.1016/j.cscm.2021.e00780.

[30] L. Yang, S.M.E. Sepasgozar, S. Shirowzhan, A. Kashani, and D. Edwards, "Nozzle criteria for enhancing extrudability, buildability and interlayer bonding in 3D printing concrete", *Automation in Construction*, vol. 146, 2023, doi: 10.1016/j.autcon.2022.104671.

[31] H. Chen, D. Zhang, P. Chen, N. Li, and A. Perrot, "A Review of the Extruder System Design for Large-Scale Extrusion-Based 3D Concrete Printing", *Materials*, vol. 16, no. 7, art. no. 2661, 2023, doi: 10.3390/ma16072661.

[32] M. Papachristoforou, V. Mitsopoulos, and M. Stefanidou, "Evaluation of workability parameters in 3D printing concrete", *Procedia Structural Integrity*, vol. 10, pp. 155–162, 2018, doi: 10.1016/j.prostr.2018.09.023.

[33] S. Alonso-Canon, E. Blanco-Fernandez, D. Castro-Fresno, A.I. Yoris-Nobile, and L. Castañon-Jano, "Reinforcements in 3D printing concrete structures", *Archives of Civil and Mechanical Engineering*, vol. 23, art no. 25, 2023, doi: 10.1007/s43452-022-00552-z.

[34] F. Bester, M. van den Heever, J. Kruger, and G. van Zijl, "Reinforcing digitally fabricated concrete: A systems approach review", *Additive Manufacturing*, vol. 37, 2021, doi: 10.1016/j.addma.2020.101737.

[35] V. Mechtcherine and V.N. Nerella, "Integration der Bewehrung beim 3D-Druck mit Beton", *Beton- und Stahlbetonbau*, vol. 113, no. 7, pp. 496–504, 2018, doi: 10.1002/best.201800003.

[36] C. Zhang, V.N. Nerella, A. Krishna, S. Wang, Y. Zhang, V. Mechtcherine, and N. Banthia, "Mix design concepts for 3D printable concrete: A review", *Cement and Concrete Composites*, vol. 122, 2021, doi: 10.1016/j.cemconcomp.2021.104155.

[37] C. Ziejewska, J. Marczyk, K. Korniejenko, et al., "3D Printing of Concrete-Geopolymer Hybrids", *Materials*, vol. 15, no. 8, art. no. 2819, 2022, doi: 10.3390/ma15082819.

[38] S. Skibicki, M. Pułtorak, M. Kaszyńska, M. Hoffmann, E. Ekiert, and D. Sibera, "The effect of using recycled PET aggregates on mechanical and durability properties of 3D printed mortar", *Construction and Building Materials*, vol. 335, 2022, doi: 10.1016/j.conbuildmat.2022.127443.

[39] M. Kaszyńska, S. Skibicki, and M. Hoffmann, "3D Concrete Printing for Sustainable Construction", *Energies*, vol. 13, no. 23, art. no. 6351, 2020, doi: 10.3390/en13236351.

[40] I. Mai, L. Brohmann, N. Freund, et al., "Large Particle 3D Concrete Printing—A Green and Viable Solution", *Materials*, vol. 14, no. 20, art. no. 6125, 2021, doi: 10.3390/ma14206125.

[41] S. Bhattacherjee, A.S. Basavaraj, A.V. Rahul, et al., "Sustainable materials for 3D concrete printing", *Cement and Concrete Composites*, vol. 122, 2021, doi: 10.1016/j.cemconcomp.2021.104156.

[42] N.J. van Eck and L. Waltman, "VOSviewer Manual. Manual for VOSviewer version 1.6.20", 31 October 2023. [Online]. Available: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.20.pdf. [Accessed: 21. Nov. 2023].

[43] T. Mader, M. Schreter-Fleischhacker, O. Shkundalova, M. Neuner, G. Hofstetter, "Constitutive modeling of orthotropic nonlinear mechanical behavior of hardened 3D printed concrete", *Acta Mechanica*, vol. 234, pp. 5893–5918, 2023, doi: 10.1007/s00707-023-03706-z.

[44] L. Jendele, J. Cervenka, and M. Herzfeldt, "FEM modelling of digitally printed concrete structures using 3D extrusion", in *Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications: Proceedings of the 7th International Conference on Structural Engineering, Mechanics and Computation (SEMC 2019), September 2–4, 2019, Cape Town, South Africa*, A. Zingoni, Ed. CRC Press, 2019, pp. 431–436, doi: 10.1201/9780429426506-77.

[45] G. Rizzieri, L. Ferrara, and M. Cremonesi, "Numerical simulation of the extrusion and layer deposition processes in 3D concrete printing with the Particle Finite Element Method", *Computational Mechanics*, vol. 73, pp. 277–295, 2024, doi: 10.1007/s00466-023-02367-y.

[46] D. Kajzr, T. Myslivec, and J. Cernohorsky, "An Open PLC-Based Robot Control System for 3D Concrete Printing", *Robotics*, vol. 12, no. 4, 2023, doi: 10.3390/robotics12040096.

[47] M. Hoffmann, S. Skibicki, P. Pankratow, A. Zieliński, M. Pajor, and M. Techman, "Automation in the Construction of a 3D-Printed Concrete Wall with the Use of a Lintel Gripper", *Materials*, vol. 13, no. 8, 2020, doi: 10.3390/ma13081800.

[48] "Advanced Search". [Online]. Available: https://patents.google.com/advanced. [Accessed: 21. Nov. 2023].

[49] "European Patent Register >Country codes". [Online]. Available: https://register.epo.org/help?lng=en&topic=countrycodes. [Accessed: 21. Nov. 2023].

[50] "Visegrad Fund ->News". [Online]. Available: https://www.visegradfund.org/news/visegrad-focus-research-development-innovation-digitalization/reg/. [Accessed: 13. Dec. 2023]

[51] "Interreg 2021-2027: Fostering Cooperation for a Stronger Europe". [Online]. Available: https://interreg.eu/about-interreg/. [Accessed: 13. Dec. 2023].

Trójwymiarowe drukowanie z betonu – regionalne możliwości i wyzwania

Słowa kluczowe: 3DCP, drukowanie betonu, techniki przyrostowe

Streszczenie:

Artykuł ma na celu zidentyfikowanie naukowych i przemysłowych perspektyw rozwoju druku 3D z betonu, ze szczególnym uwzględnieniem potencjału regionalnego. Główną metodą badawczą było studium literatury przedmiotu wzbogacone o ankietę bibliometryczną i analizę dotyczącą środków ochrony własności intelektualnej. Na potrzeby badania bibliometrycznego zebrano szczegółowe dane na temat publikacji dotyczących wytwarzania przyrostowego betonu. Zebrane informacje obejmowały między innymi: rok publikacji, zakres, autorów wraz z afiliacjami, cytowania itp. Dane zostały przeanalizowane w zadanych zbiorach i podzbiorach w celu identyfikacji wzajemnych relacji i ścieżek wpływu. Jako narzędzie pomocnicze do studium, utworzono chmurę tagów i przeprowadzono jej analizę. Ponadto, przeanalizowano bazę danych patentów oraz dokumentów dotyczących ochrony własności intelektualnej odnoszących się do drukowania z betonu, aby zapewnić pewien wgląd w potencjał do wdrożeń przemysłowych i komercjalizacji. Wyniki pozwoliły stwierdzić, które aspekty wydają się być najbardziej istotne dla rozwoju nauki i zastosowania druku 3D z betonu. Określono propozycje kierunków dla dalszych badań, biorąc pod uwagę również wdrożenia przemysłowe. Przedstawione wyniki mogą być wykorzystane jako wytyczne dla partnerów naukowych i przemysłowych z regionu.

Received: 2023-12-19, Revised: 2024-06-10