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Review

A Review of the Digital Skills Needed in the Construction Industry: Towards a Taxonomy of Skills

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Abstract: The construction industry is slowly embracing digitalisation in line with the Industry 4.0 revolution and the aftermath of the COVID-19 pandemic. However, progress has been sluggish due to stakeholders' limited awareness of digital skills. This study addresses this issue by developing a comprehensive taxonomy of digital skills required to successfully implement the Industry 4.0 principles of digitalisation in the construction industry. A systematic literature review was conducted by mining the Scopus and Web of Science databases to identify relevant literature and map the skills currently used or needed for digitalisation. The study also examined publication trends and outlets to gain insight into developments. Additionally, VOSviewer was used to conduct a scientometric analysis of the shortlisted articles to identify important keywords and authorship collaboration networks within this research domain. A total of thirty-five digital skills were identified from the literature. These skills were organised into a taxonomy with categories named automation and robotics, coding and programming, design, drafting and engineering, digital data acquisition and integration, digital literacy, digitisation and virtualisation, modelling and simulation, and planning and estimation. The developed taxonomy will help stakeholders plan strategically to provide digital skills to the new graduates joining the workforce, enabling a more comprehensive approach to the digitalisation of the construction industry.

Keywords: construction industry; digital skills; digitalisation; Industry 4.0; systematic literature review; scientometric analysis; taxonomy

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1. Introduction

Digitalisation involves converting the existing manual processes into automated, self-regulated digital processes using information and communication technology (ICT) tools, techniques, and practices. However, digital technologies have a broad and diverse definition that can vary depending on an individual's needs, situation, and relationship with the technology. Therefore, digital technologies, for instance, building information modelling (BIM), augmented reality (AR), and virtual reality (VR), may mean different things to different people. Moreover, these technologies, which consist of hardware and software, can serve multiple purposes and be utilised throughout various phases of a construction project [1].

Several industries, including manufacturing, retail, and banking, have recognised the benefits of digitalisation [2]. However, the construction industry has yet to adopt it and reap its usefulness fully [3–5], even in developed countries such as Australia [6]. The globally existing and fast-paced digitalisation in the context of Industry 4.0 or the digital revolution [5] urges the construction industry to transform rationally for efficient performance [7]. Disruptive changes have occurred in the construction sector, starting with transitioning from manual to computer-aided design (CAD) and then to BIM. Other digital technologies, including the Internet of Things (IoT), AR, VR, artificial intelligence (AI), drones, laser scanning, 3D printing, big data analytics, geographic information systems (GIS), and robotics, are the applications of the Industry 4.0 concepts [8–15]. These technologies help further achieve modern-era sustainable solutions such as a circular economy within the construction supply chain [16,17]. However, they have limited and slower adoption in the construction sector [18,19]. Nevertheless, these technologies help eliminate many of the inefficiencies of complex construction projects [18], improving the performance of the construction projects [13], such as safety and quality [20].

Researchers report that adopting digital technologies and the transition towards Industry 4.0 is hindered by a lack of skills, knowledge, expertise, and experience [6,18,21–23]. These barriers affect the individual's and firm's performance [14]. This claim is backed by research that indicated that roughly 7.5% of time loss occurs due to malfunctioning of the ICT devices because of a lack of ICT skills among the workers [24]. Furthermore, Francis and Paton-Cole [25] emphasised the Victorian government's findings that approximately 75% of construction industry employers believe technical and job-specific skills are lacking in the industry [26], which affects project costs and productivity [27]. Several other authors, such as Becker et al. [28] and Djumalieva and Sleeman [29], also point out that digital skills are and will be required for most jobs. Suprun et al. [18] reported that the existing skills gap might appear more significant soon as digital technologies and relevant skills needed keep evolving. To this point in time, there is an overwhelming demand for digital skills in the labour market [30]. Hence, enhanced skill sets should be provided to the site personnel and higher management [31] to manage the challenges faced by Industry 4.0 in the construction industry [7].

The research and application landscapes are changing in the construction industry domain, for example, Industry 4.0 applications [32,33], digitalisation, and the utility of AI for innovation in construction firms [34]. The evolution of information technology (IT) related applications ranges from generic internet and email access to architecture, engineering, and construction (AEC) specific applications such as foundational design and code compliance checking [35,36]. Relevant emerging technologies are adapted in almost all the project lifecycle phases and add value to the projects [37]. Implementing IT-based systems in a construction organisation faces risk factors such as time limitations and lack of training; however, it could be managed by maintaining dedicated IT professionals on the project [38]. Still, on average, AEC firms invest less in innovation and give it less significance than their counterparts in advanced industries such as IT and electronics [39]. It is evident from past research [40] that dedicated developers work on software development applicable to various domains, including the construction industry. However, the developed framework consists of cyclic efforts to reach a consensus to design the intended application outcome [40].

Nonetheless, the abovementioned IT advancements have enabled computing to become an increasingly vital component within AEC disciplines [41,42] and, consequently, have pushed the construction industry stakeholders to improve their state of innovation and automation through indigenous human resources [43,44]. As a result, more digitalisation and automation skills are deemed necessary and taught through formal and informal training to construction professionals, making this a development field. It allows the construction industry to develop technological tools that are better suited to the construction industry [45]. In this regard, the increasing number of publications on digitalisation-related topics in recent years attests to researchers' growing interest in the subject, indicating that such topics contribute significantly to the construction industry's worldwide development [46]. With the practical application of Construction 4.0 technologies and practices, including BIM, AR, and VR, the relevant requirement for a new set of skills within the sector's human resources is also evolving [6,47]. However, at the same time, this evolved skillset requirement is a challenge for the industry, academia, and government [5,33,48]. This shift towards digitalisation and the pressing need for relevant skills is further evident through grey literature [49–51]. As a result, computing and programming skills are being increasingly considered and taught to upcoming civil and construction graduates [52,53].

These arguments show that the construction industry's skills requirements have emerged and evolved. Stakeholders have continuously tried to assess the workforce skills requirements to acknowledge the criticality of issues due to the skills shortage and propose and implement skills development strategies and practices [54,55]. It presents the further need for an updated evaluation of digital skills. Also, it will be evident from the subsequent sections that various digital skills are available in the literature but in an isolated form. An effective categorisation of the identified digital skills has been missing. In the absence, the relevant academic and industry stakeholders struggle to target the training and upskilling of the workforce fur future needs. Consequently, this research aims to synthesise the state of the literature on the digital skills currently used or needed across a range of job roles and professions, including design, estimation, planning, and scheduling, to name a few, in the broader construction industry domain and to develop the taxonomy of digital skills per the construction industry needs. This taxonomy will help academia and industry to focus on the presently demanded digital skills.

2. Methodology

This study utilised scientometric analysis and a systematic literature review (SLR) methodology to synthesise the literature's state and develop the digital skills taxonomy, as presented in the flowchart (Figure 1). Scientometric analysis involves quantitative and qualitative methods to analyse the structure, evolution, and impact of scientific knowledge [56]. In this study, the scientometric method was used to examine the publication patterns, trends and outlets in the field of construction management, as covered by several authors [57–59]. The data collected were further analysed to identify the most frequently studied topics and authors and map the relationships between different scientific fields and authors, i.e., co-occurrence and co-authorship networks. VOSviewer was used for this purpose.

VOSviewer is a freely available statistical tool for measuring the impact of research through bibliometric analysis and has been successfully applied across various academic disciplines. It offers basic functionalities for producing, visualising and representing scientometric networks [60]. Specifically, VOSviewer uses a graphical representation to visualise the correlation strength between nodes, with warmer colours indicating a higher or stronger correlation strength [61]. Furthermore, the visual interpretation of the relevant literature with VOSviewer can identify emergent common themes and relationships between their elements. In the construction management discipline, VOSviewer has been used successfully to analyse and visualise keyword mapping, author collaboration networks, prominent outlet mapping, country collaboration networks, and research clusters.

Conversely, SLR uses replicable methods to identify, screen, and evaluate the studies undertaken in the research area [62]. Furthermore, as an enormous amount of research is produced for each research area, delineating a fine line between what is done and the possible research gaps becomes necessary. SLR can be utilised to comprehensively collate the existing works for a particular research question or aim [63–65]. The SLR procedure usually comprises the following stages: scoping, planning, searching, screening, eligibility, research syntheses, and presentation of results [63].

In the scoping and planning phases, the research focus statement was formulated, i.e., to develop a taxonomy (viz grouping, classification or categorisation) of the digital skills currently needed or utilised in the construction industry. Taxonomy in the scope of this research includes categorising skills and competencies, similar to previous studies [66,67], where the taxonomies were developed for standard soft skills and project management competencies. Based on this research theme, search keywords were brainstormed (based on a preliminary and non-systematic review of literature) and grouped under the categories "Construction Industry (C)", "Digital Skills (DS)", "Digitalisation (D)", "Systematic Literature Review

(SLR)", "Taxonomy (T)", "Education (E)", and "Stakeholders (S)". The "C" group included the keywords AEC, architectural engineering, civil/construction engineering, construction engineering and management, and construction industry/management/sector. The "DS" group included keywords such as digital skill/literacy/competence, emerging technological skill/competence, digital competence, and technology/construction 4.0 skills. The "D" group comprises digital technology/transformation, emerging technology, Industry 4.0/4th industrial revolution, and advanced construction technology. The "SLR" group consisted of content/bibliometric/meta-analysis, systematic literature review, scientometric analysis, and text mining. The "T" group contained keywords such as classification, list, and group. The other groups—"E" and "S"—consisted of keywords (phrases) with nouns from the "C" group but with the addition of words such as classroom/curricula/education/program and student/graduate/professional, respectively. The preliminary inclusion criteria were set to consider only those publications that mention the digital competencies, roles or skills related to digitalisation of the construction industry utilised or needed within the architecture, construction engineering and management industries.

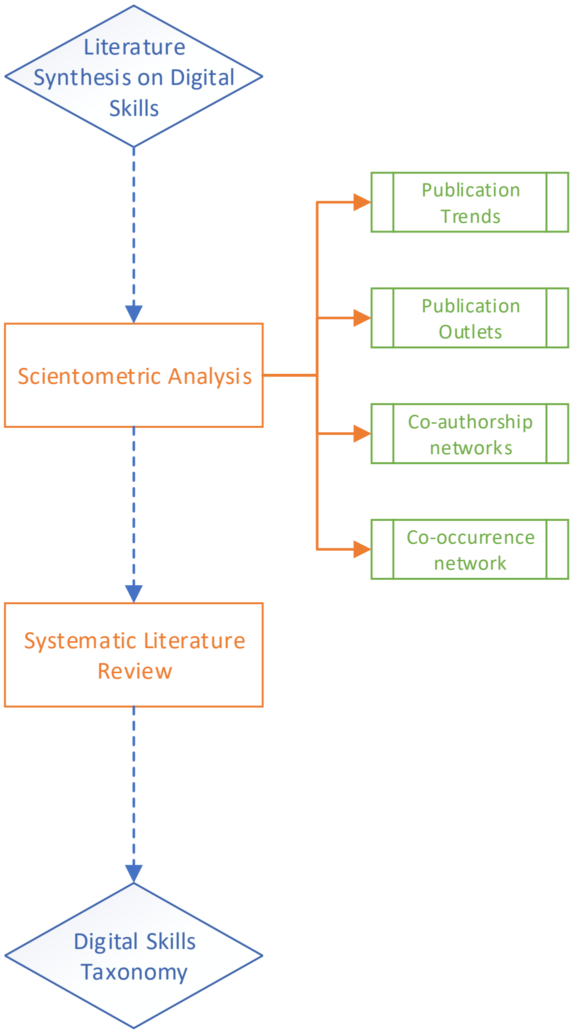

Figure 1. Flowchart of research methodology.

Several keyword combinations, for example, "C" and "DS", "DS" and "S", "DS" and "T", and "S", as presented in Appendix A, were used to search in the Scopus and Web of Science (WoS) databases, utilising title, abstract, and keyword search criteria. The Boolean operator "AND" was used between different keyword groups, while "OR" was used to control the scope within each group. While conducting the literature search, no year limit was specified in the search criteria, similar to a previous recent study [68], to include as many articles as possible. It was done to ensure a comprehensive and inclusive approach. A total of 471 records were found. After downloading the relevant records from the two databases into the MS Excel format, the records were merged, duplicates (353) were removed, and non-English language records (5) were discarded. With the title and abstract screening process, 34 articles were discarded.

Furthermore, in the detailed screening phase of the SLR, while sifting through the full versions of the 79 articles, 45 records were discarded based on the explicit inclusion and exclusion criteria. Either the articles did not consider the "digital skills" related discussion, did not mention the need or current utilisation of the research-themed skills, were related to only teaching and learning, or the full texts were unavailable. Also, during this screening phase, the scope was not specific to developing or developed countries. Therefore, articles from developed and developing countries were included to reflect the relevant literature on digital skills. Later on, the eligible records were scanned again. Through the snowballing method, which is to look at the 34 shortlisted publications' references and citations, a further 12 research publications were found to be relevant. Hence, these were included, totalling 46 articles for the final synthesis. The shortlisted articles were published between 2007 and 2023 (to date). Figure 2 summarises the above steps in the form of the preferred reporting items for systematic reviews and meta-analyses (PRISMA) model.

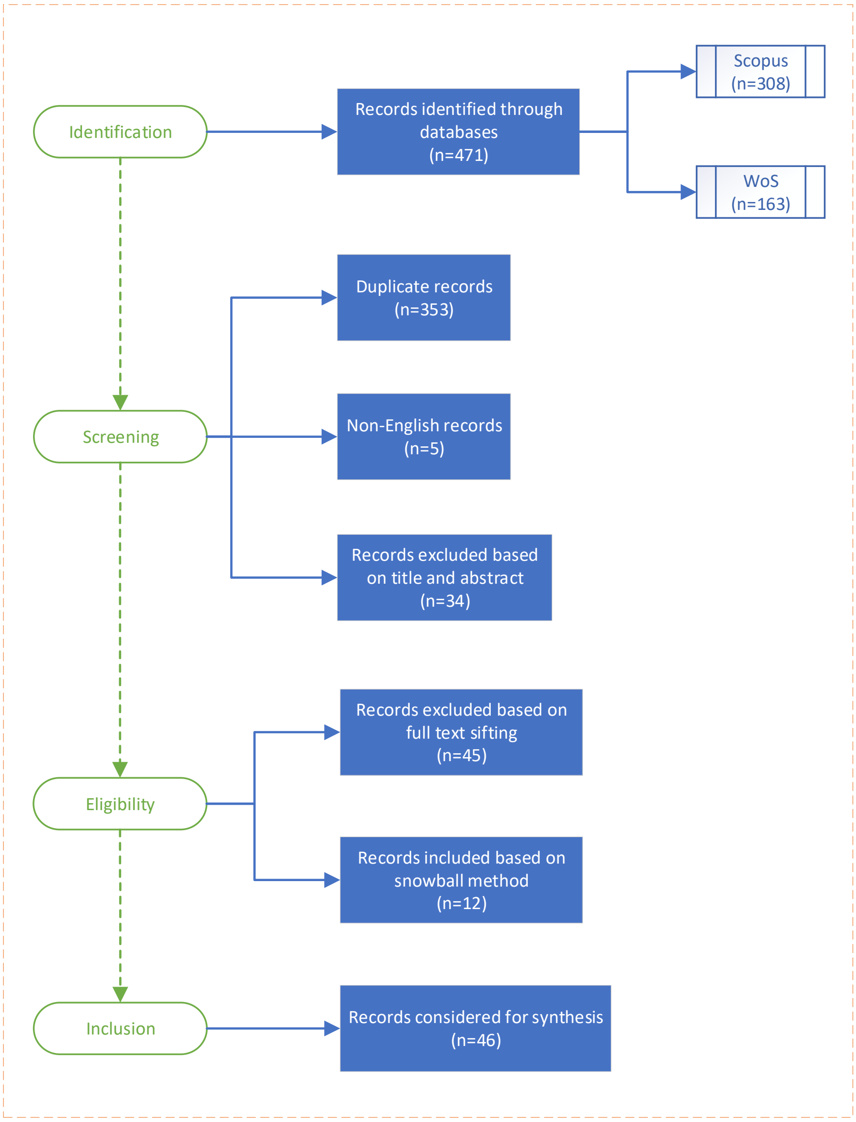

Figure 2. PRISMA flowchart.

Based on the mentioned criteria, the discarded articles consisted of irrelevant research such as small- and medium-sized enterprises' sustainability approaches and relevant educational interventions [65], digital educational tools, personalised learning, and relevant assessments of the students [69]. Furthermore, a research work [70] that focused only on the professional and pedagogical competence development of the teachers at civil engineering universities was also removed. In other research [71], road construction site managers' competencies were assessed to identify the failures, and construction management system, project administration, and resource procurement competency factors were emphasised to be improved, so it was removed as well. Moreover, human resource development strategies were ascertained in research work but with a keen focus on soft skills rather than being digital precisely [72], so they were not aligned with the scope and hence were discarded as well. Though the mentioned research works fall under the larger domain of civil engineering works and discuss the needed competencies, they still lack the targeted focus outlined in this work's scope. It shall be noted that if the keywords "DS" or "D" were to be searched in combination with "C", it would result in enormous results. However, the focus was not on the overall digitalisation in the construction industry domain or the developed digital tools and technologies. Hence, the relevant search criteria were limited to the need for or utilisation of digital skills. Therefore, all the papers not falling within this scope were removed. Furthermore, it shall be noted that it is possible to search different digital technologies or concepts, such as BIM, AR, and VR, along with the keyword "DS". However, it would yield a massive number of search results and eventually might not lead to shortlisting any other digital skill because of the already-considered keywords related to digitalisation.

3. Results and Discussion

The construction industry is undergoing the process of global digitalisation. Technological changes in the construction industry help improve the processes and tools on-site and in the design and project offices to manage projects during various lifecycle phases [1]. The possibilities are limitless, including automation of construction sites [73], digitisation of design documents, utilisation of big data for enormous data fetching and management processes, and many more. The need for relevant digital skills has also intensified due to the increasing utilisation of these and many other digital technologies in the construction sector [23]. Any ability that involves the computer and the internet can be broadly termed under the umbrella of "digital skills" [74]. They combine digital mindset, knowledge, competence, skill, and attitude [75]. Engineers with digital skills are expected to be more productive and beneficial for organisations [15].

3.1. Publication Trends

From analysing the considered publications, as presented in Figure 3, the results show an equal number of conference proceedings and journal articles, with 22 publications each. In addition, there are two book chapters in the dataset.

Furthermore, the trend shown in Figure 4 points to a variation in the number of annual conference and journal articles published. Initially, a conference paper trend was observed until the year 2021, whereas, from 2019, journal publications were also evident. The year 2021 saw the highest number of publications (8 altogether). Specifically, the highest number of conference publications (4) was found in 2020, while for journal articles, the highest number (7) was in 2022. The years 2014, 2019, and 2021 observed three conference publications each year.

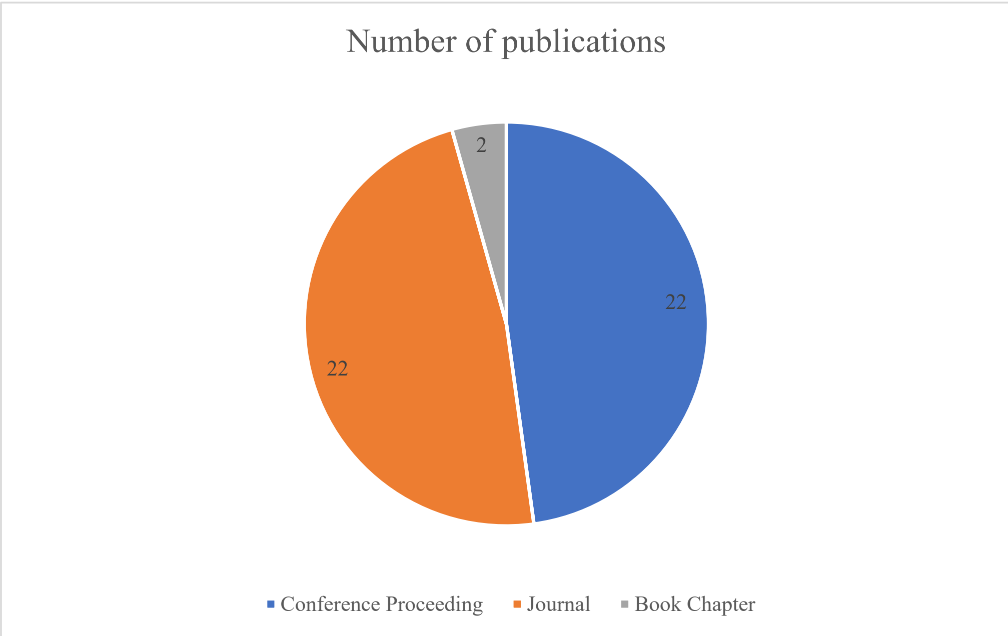

Figure 3. Number of publications.

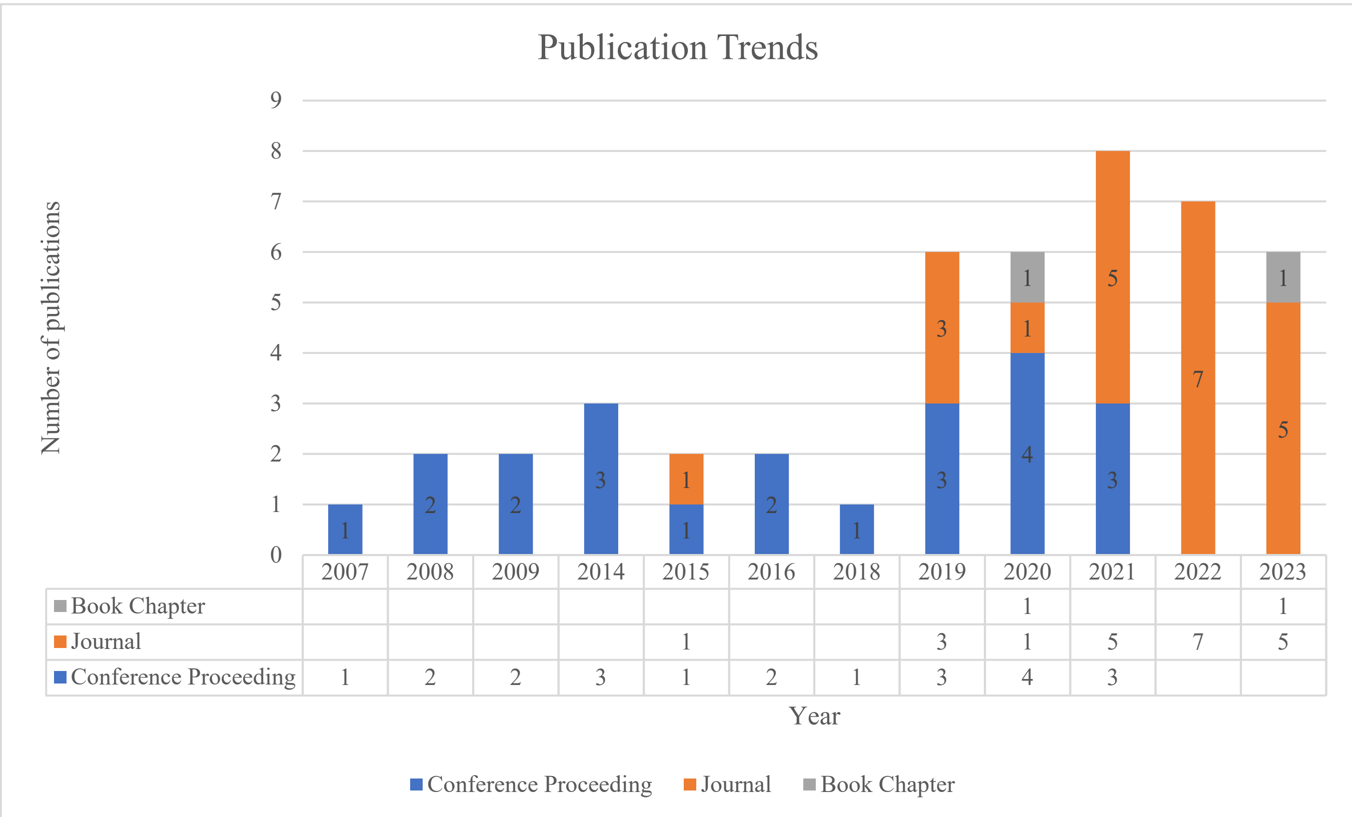

Figure 4. Publication trends.

On the other hand, in 2021 and 2023, five publications each were noted as journal articles. In 2020 and 2023, there were relevant publications in the form of a book chapter, the only ones found in the current dataset. It is realised from the results that conference publications specifically saw two peaks: in 2014 and 2020. In comparison, journal articles were more frequent in the later years. One of the possible interpretations could be the urge of researchers to present their works with limited supporting literature to the appropriate peers and audience in the form of a conference and gain early feedback for improvement [76,77]. It also provides quicker dissemination of relevant knowledge as the turnaround time of conference papers is significantly lower than those published in academic journals. Though the conference papers are easier to publish, they are still peer-reviewed by experts in the field, providing quality control. However, this further suggests that future researchers in this area could also consider publishing in academic journals to achieve a wider reach and rigorous critique for better quality and outcome.

3.2. Publication Outlets

Table 1 presents the distribution of the publications in the respective academic outlets. The results show that the authors of the articles have published in a diverse range of outlets, including both conference proceedings and academic journals. The authors have contributed significantly to the body of knowledge in their field by disseminating their research through various outlets. Among the conference publications, the *American Society for Engineering Education* (*ASEE) Annual Conference & Exposition* was the most popular outlet, with four publications. The *Royal Institution of Chartered Surveyors (RICS) Construction and Building Research Conference*, *IEEE International Conference on Emerging eLearning Technologies and Applications*, and *International Conference of Education, Research and Innovation* had two publications each. Whereas for the journal articles, the journal '*Buildings*' had the most (3) publications. After that, the journals '*Journal of Construction in Developing Countries*', '*International Journal of Construction Management*', and '*Journal of Management in Engineering*' observed two publications. The remaining journals and conference outlets had one publication each in the considered dataset. It points to the lack of interest in mainstream construction digitalisation journals, for example, *Automation in Construction*, in publishing education and skills-related research on construction digitalisation because of the limitation of their scope. It involves using ICT in design, engineering, and construction technologies and maintaining and managing the built environment [78].

Table 1. Frequency of publication outlets.

Outlet	**Count of Publications**
ASEE Annual Conference & Exposition	4
Buildings	3
Journal of Construction in Developing Countries	2
International Journal of Construction Management	2
Journal of Management in Engineering	2
RICS Construction and Building Research Conference	2
IEEE International Conference on Emerging eLearning Technologies and Applications (ICETA)	2
International Conference of Education, Research and Innovation (ICERI)	2
Journal of Civil Engineering Education	1
International Journal of Construction Education and Research	1
Nanotechnologies in Construction A Scientific Internet-Journal	1
Frontiers in Built Environment	1
IOP Conference Series: Earth and Environmental Science	1
IEEE International Conference on Advanced Learning Technologies (ICALT)	1
Journal of Engineering, Design and Technology	1
Australasian Association for Engineering Education (AAEE) Annual Conference	1
Engineering Management Journal	1
Industry and Higher Education	1
American Society of Civil Engineers (ASCE) Construction Research Congress	1
Infrastructures	1

Table 1. *Cont.*

Outlet	Count of Publications
IOP Conference Series: Materials Science and Engineering	1
Routledge, Taylor & Francis Group, Informa UK Limited	1
Built Environment Project and Asset Management	1
South African Journal of Science	1
EAI/Springer Innovations in Communication and Computing	1
Transportation Research Record: Journal of the Transportation Research Board	1
Procedia—Social and Behavioral Sciences	1
AIP Conference Proceedings	1
Engineering, Construction and Architectural Management	1
International Conference on Intellectual Capital, Knowledge Management and Organisational Learning (ICICKM)	1
Sustainability	1
International Conference on Computers in Education (ICCE)	1
World Congress on Engineering (WCE)	1
International Conference on Education and New Learning Technologies (EDULEARN)	1
International Conference on Industrial Engineering and Operations Management	1

Similarly, the *Journal of Computing in Civil Engineering* focuses on innovative and novel ideas in computing applicable to the engineering profession. These may include innovations in artificial intelligence, parallel processing, distributed computing, graphics and imaging, and IT [79]. So, this limitation practically directs the research published in such journals towards technology innovation and application. However, to improve the academic aspects of skill development, these outlets may broaden their scope to accommodate high-quality research on digital skills for a much more extensive reach rather than limiting to solution development or application-oriented research.

Besides that, there are other significant publication outlets for researchers in the construction education area, which could be aimed at publishing research related to *the need for relevant skills*. For example, the *Journal of Civil Engineering Education* and the *International Journal of Construction Education and Research* are some of the many outlets. The *Journal of Civil Engineering Education* focuses on research related to effective methods to teach civil engineering principles and prepare students through formal education, teaching practice issues, ethics education, case studies of pedagogy, and lessons learned that are unique to the civil engineering practice [80]. Similarly, the *International Journal of Construction Education and Research* contributes to understanding issues and topics associated with construction education and the construction industry. The journal's scope also embraces workforce development and pedagogical content [81].

3.3. Co-Authorship Networks

The scientometric analysis investigated the authors' co-authorship networks. Awareness of collaborative teams and authors in any research area boosts the effectiveness and efficiency of scholarly works [82]. Glänzel and Schubert [83] reasoned that the established networks of authors help publish the articles in good outlets, resulting in more citations. Thus, a co-authorship network is generated via VOSviewer. The type of analysis chosen was co-authorship. The unit of analysis was set to 'authors' and the counting method to 'fractional counting' to select the top investigators. An author's minimum number of documents was set to one to get an overall view. There were 136 authors altogether. When processed for analysing, two networks were generated. One consists of all the authors (Figure 5), whether interconnected or not; the second consists of seven items (Figure 6) when the software tool prompts for the set of connected items only.

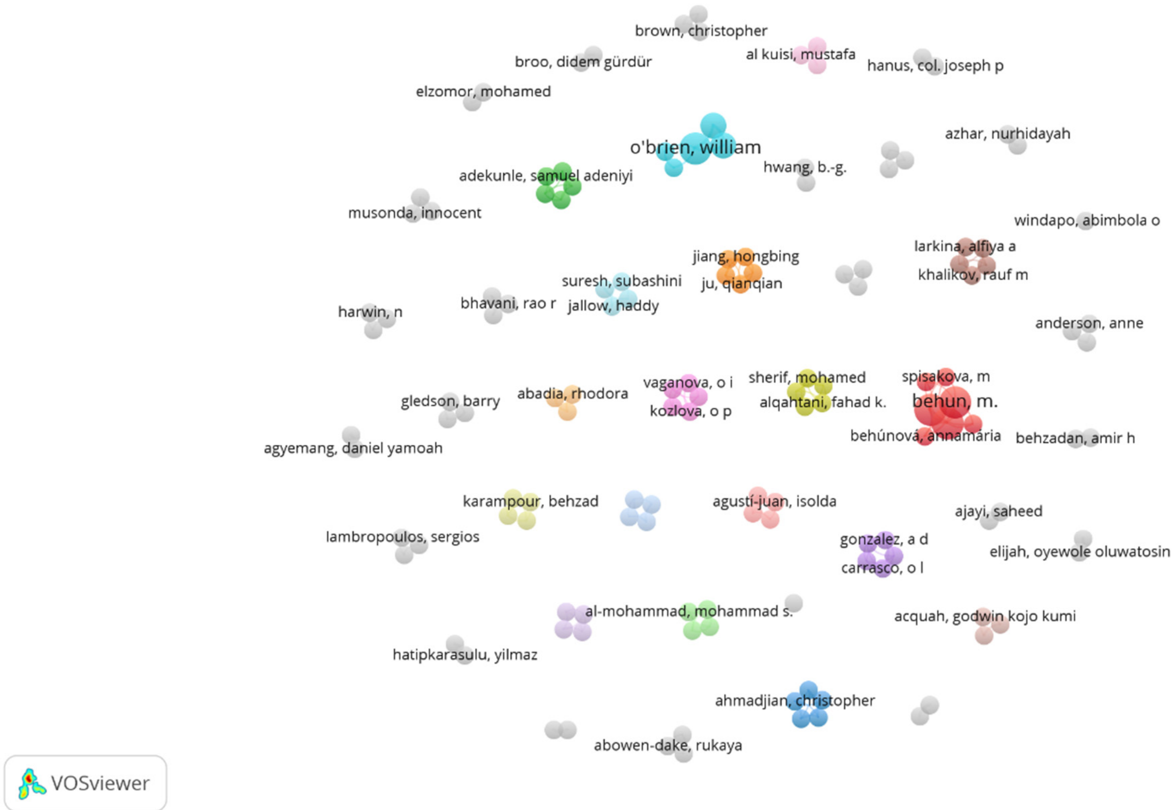

Figure 5. Co-authorship network of all authors.

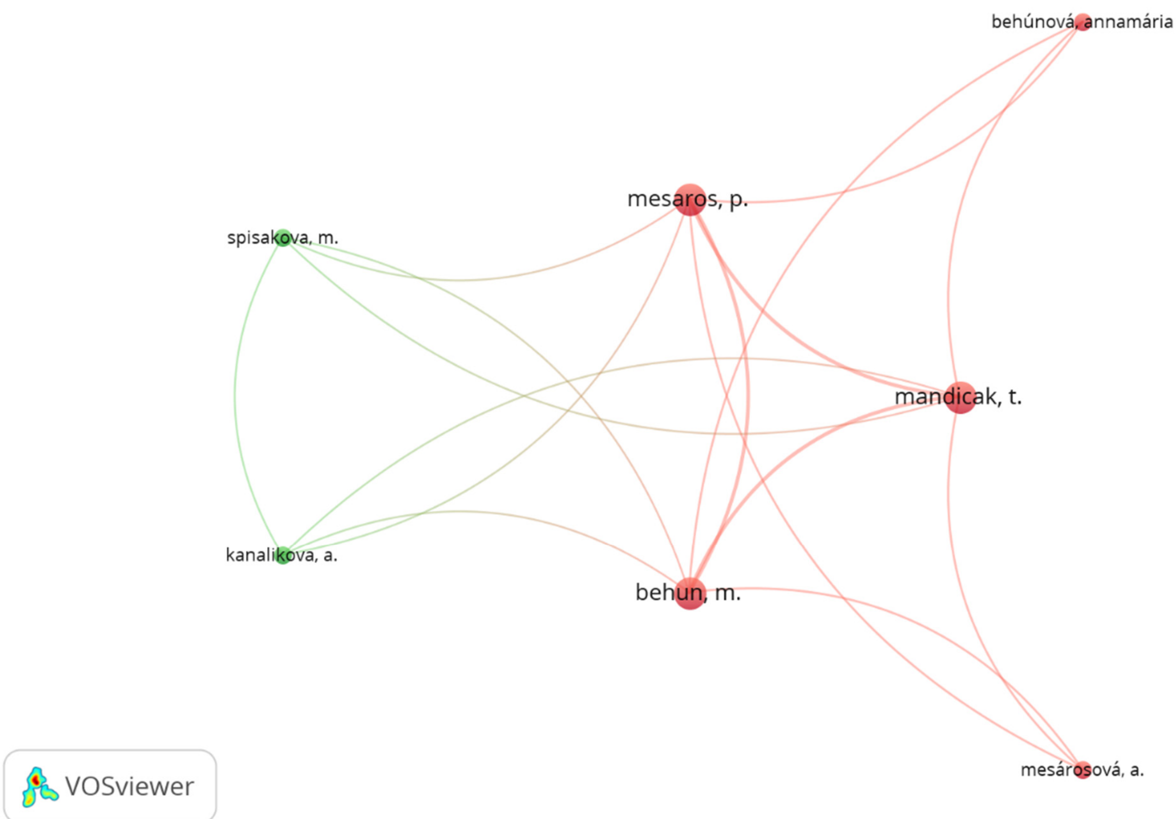

Figure 6. Co-authorship network of connected authors.

Figure 5 shows the network map of 136 authors in 42 clusters, the most extensive of which is seven authors. Most authors are not interconnected, except for being co-author of each other in the same publication. It depicts that not much of a research network is currently established in the research race to present the digital skills required for the construction industry. One prospective explanation could be that the authors focus on and assess the lack of digitalisation or relevant need for skills limited only to their institutes, companies, or regions. Another possible reason for this lesser collaboration is that this research area requires interdisciplinary collaboration. The research on digital skills demands that researchers of traditional fields such as civil engineering, construction and architecture join hands with modern fields, for example, ICT, under the stewardship of researchers of education and training. Understandably, interdisciplinary collaboration comes with logistic challenges, such as identifying and connecting with potential collaborators, establishing working relationships, demonstrating mutual value, and traversing through sector-specific jargon. Since researchers tend to work in silos, achieving this interdisciplinary collaboration is more challenging than perceived. While several researchers work on digital construction topics, digital skills and their provision to young graduates see less action, mainly due to the need for three research dimensions: AEC, ICT, and education.

Figure 6 presents that only seven authors are interconnected with each other. Mandicak T, Behun M, and Mesaros P are the most prominent authors. They are connected with six other authors. The *total link strength* for each mentioned author is 3, meaning they have co-authored three documents. Spisakova M and Kanalikova A, are found to be co-authors of each other along with the three prominent ones, but in only one publication. In contrast, Behunova A and Mesarosova A are co-authors with the previously mentioned three prominent authors through one document each but without sharing the same document authorship with each other. On investigating their relevant articles, it is realised that they have worked on the research areas of digital competencies, including BIM, amongst the construction project management stakeholders [84–86].

Furthermore, Mandicak T, Mesaros P, and Spisakova M are affiliated with the Department of Economics, Management and Information Systems in Construction, Faculty of Civil Engineering, Technical University of Košice, Košice, Slovakia. In contrast, Kanalikova A is with the Department of Applied Mathematics and Descriptive Geometry at the same university. At the same time, Behun M and Behunova A are affiliated with the same university but with the Institute of Earth Resources, Faculty of Mining, Ecology, Process Control and Geotechnologies and the Department of Industrial Engineering and Informatics, respectively. Mesarosova A, on the other hand, belongs to the Department of Audiovisual Communication, Documentation and History of Art, Polytechnic University of Valencia, Spain. From the connections, it is evident that the collaboration mainly remained amongst different researchers within the multiple departments of the same university and country, except for an author from a Spanish university.

3.4. Co-Occurrence Network

Keywords highlight the foundational concept in an article and provide a way to figure out the main knowledge areas within a particular research domain [87,88]. Following the opted methodology, the shortlisted documents were imported into VOSviewer to identify the main keywords or clusters. The type of analysis chosen was 'co-occurrence'. The unit of analysis was set to 'keywords' and the counting method to 'fractional counting'. The minimum number of occurrences of a keyword was set to two. If only one was chosen, too broad concepts (in terms of keywords) would be highlighted, which may not reveal much meaningful analysis. Similar words or synonyms were also merged, such as "BIM", "building information modelling", or "building information modeling".

There were 118 keywords altogether. With the condition of two occurrences of keywords, only twelve met the threshold. The resulting network is presented in Figure 7, which shows twelve items formed into 4 clusters with 21 links. The first cluster consists of the keywords: "BIM", "BIM adoption", and "BIM barriers". Another set involves

"Competence", "Construction professionals", and "Digital literacy". After that, cluster 3 consists of "Construction industry", "Artificial intelligence", and "Skills", and the last set consists of keywords "Construction management students", "skill gaps", and "training needs". "Construction industry" and "BIM" are the central keywords here, with seven links each. The "Construction industry" keyword centralises around the need of construction stakeholders to improve their existing skills and competence set to modern technologies such as BIM and AI. It is also realised from this network diagram how the concept of BIM is quite central to most of the other relevant ideas, be it the adoption of technology and barriers in the construction industry or the overall digital literacy improvement of the relevant stakeholders. BIM is also interconnected with the "Skills" and "training needs" keywords, emphasising the importance of this skill for construction industry professionals.

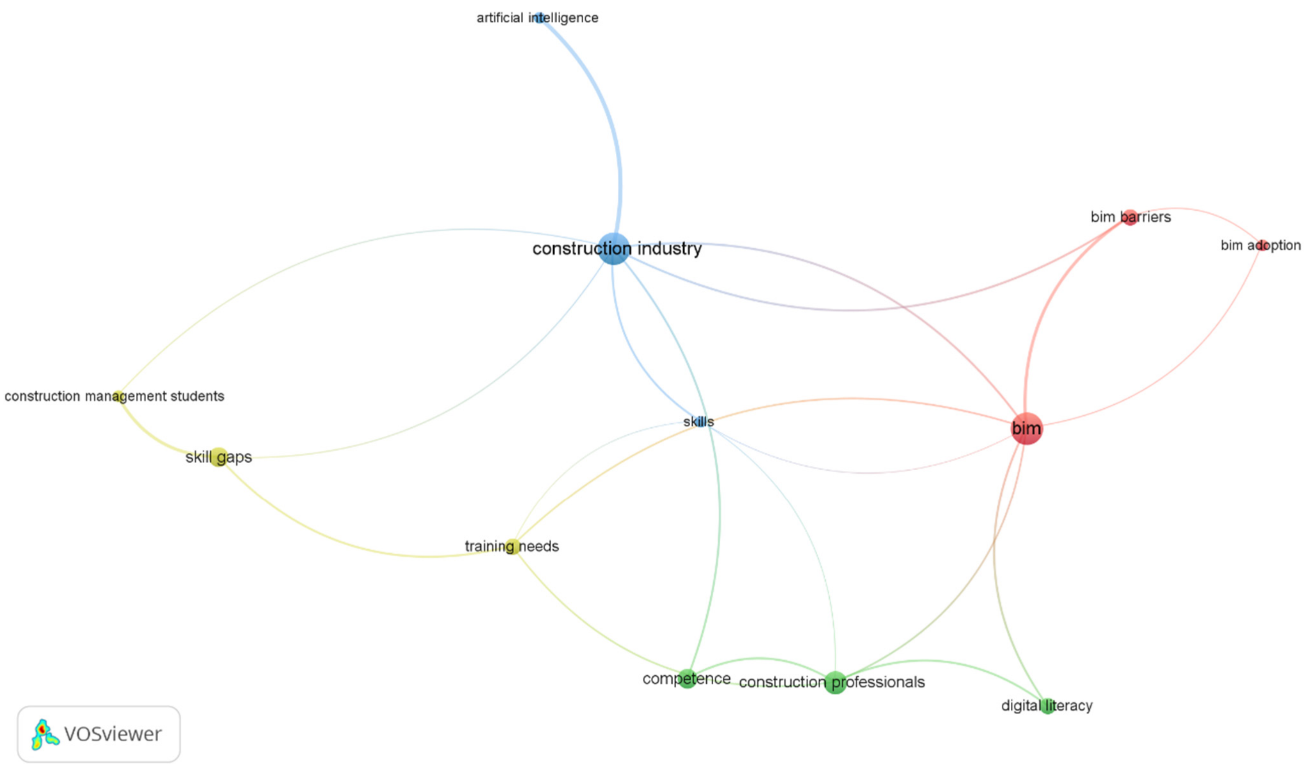

Figure 7. Co-occurrence network of keywords.

3.5. *Taxonomy of Digital Skills*

In the literature, different terminologies have been used to refer to a particular digital skill. Hence, grouping or categorising these skills is done in this research for easy understanding. However, it is essential to note that numerous categorisations could be possible. Even overlapping is likely, based on a researcher's approach and the scope of the study, i.e., a few of the digital skills in this study might be in a different category than the original category in the selected literature. In addition, a generic and broad term can be used for almost all the mentioned skills, i.e., "digital technological skills".

Nonetheless, Table 2 presents the list of digital skills and categories. The second column consists of categories: automation and robotics; coding and programming; design, drafting, and engineering; digital data acquisition and integration; digital literacy; digitisation and virtualisation; modelling and simulation; and planning and estimation. These categories were formed partially based on inspiration from [14,31] and authors' brainstorming sessions [89]. Finally, the third column consists of digital skills and is titled "Skills related to the use of" as it enlists various digital technologies, concepts, and software. Furthermore, the following section discusses individual categories and the relevant digital skills presented in Table 2, focusing on their current widespread utility and application in the larger construction industry domain. The discussion further directs towards the practical implication that digital skills must be well considered and comprehended for the fast-paced digitalisation of the construction sector.

3.5.1. Automation and Robotics

Growing advancements in the sector recently have increased the usage of several tools and methodologies such as 3D printing, automation-based technologies, autonomous vehicles, offsite construction and manufacturing, and drones/unmanned aerial vehicles (UAVs) [23,90–92]. For instance, UAVs have become increasingly popular in the construction industry for safely capturing data and generating 3D maps of construction sites [93]. With high-resolution cameras, these drones can quickly and efficiently capture images of construction sites from various angles and heights. The data collected can then be used to create accurate and detailed 3D maps of the site, which can be helpful for project planning, site analysis, and communication with stakeholders [73]. In addition, another digital technology, 3D printing, is becoming increasingly important in the construction industry as it has the potential to positively influence the industry by providing benefits such as fast construction, reduced material waste, less labour-intensive requirements, and improved worksite safety, as comprehensively summarised by Hossain et al. [91].

Furthermore, integrating automation and robotics technologies in the construction sector has improved cost, safety, quality and productivity [5,94]. New roles and responsibilities are also established whenever modern technologies are introduced in any industry. Robotics and automation in construction will create new opportunities and roles, specifically during the transition phase of human–machine interaction. Gerbert et al. [95] claim that new job positions will be more digital. For example, digital fabricator, digital coordinator, digital manager, and digital programmer will be a few of the latest roles [5]. The emphasis is on the fast-approaching digital construction era in which digital technologies and the need for digital skills are evident [18].

Table 2. Categorisation of skills.

S. No	Category	Skills Related to the Use of	Reference
1	Automation and Robotics	3D printing	[23,73]
2		Automation-based technologies	[73]
3		Autonomous vehicles	[23]
4		Digital fabrication	[5]
5		Managing and coordinating digital fabrication	
6		Drones/UAVs	[23,73,93]
7		Offsite construction and manufacturing	[23]
8		Robotics	[23,73]
9	Coding and Programming	AI	[23,73,96–98]
10		Computer programming techniques	[18,22,73]
11		Digital fabrication programming	[5]
12		Machine learning	[23,73]
13	Design, Drafting, and Engineering	AutoCAD	[5,22,99]
14		Nanotechnologies	[100]
15		Structural design/software systems designing technical solutions	[22,101]
16	Digital Data Acquisition and Integration	IoT	[23,73]
17		Smart sensors	
18		IT/ICT/computer information systems	[99,101–110]
19		Smart wearables	[23]

Table 2. *Cont.*

S. No	Category	Skills Related to the Use of	Reference
20	Digital Literacy	Computational tools/techniques; computer skills; Microsoft Office; construction software usage; awareness of and knowledge to use state-of-the-art construction technologies	[22,85,93,99,101–105,111–118]
21	Digitisation and Virtualisation	Big data	[18,23,97,103]
22		Blockchain	[23,97]
23		Cloud computing and collaboration	
24		Data analytics	[18,23]
25		Data driven digitalisation	[22]
26		GIS	[18]
27		Laser scanning	[23]
28		Lidar survey scanner	
29	Modelling and Simulation	BIM design and modelling	[5,18,21–23,85,86,101–104,118–128]
30		Digital twin	[23,129]
31		MR/AR/VR	[23,73,97,103,130]
32		Revit	[99]
33		Simulation	[131]
34	Planning and Estimation	Productivity planning apps/software	[23]
35		Scheduling and cost estimating/management via technology and software, e.g., Navisworks	[22,84,99,104,115,118]

3.5.2. Coding and Programming

The machine learning algorithms and AI concepts are mainly based on programming skills. Various benefits of programming skills can be ascertained through the literature. Kaiafa and Chassiakos [132] developed a comprehensive model in MS Excel for achieving optimal solutions to multi-objective resource-constrained project scheduling problems. The model used Visual Basic for an application-programmed genetic algorithm and aimed to minimise additional costs due to resource overallocation and day-to-day fluctuations. In addition, digital fabrication programming skills are required when robotic systems are designed for an autonomous construction industry [5]. Furthermore, BIM-based formwork and cladding quantity take-off were performed through a visual programming tool, Dynamo [133]. Also, AI's implementation areas in the construction industry were collated by Darko et al. [134], such as modelling, forecasting, simulation, and decision-making. Similarly, existing AI implementation and its benefits were assessed in the UK's construction industry. It was recommended that organisations consider AI's implementation in the future to become competitive [98].

Furthermore, developing construction industries such as South Africa were also assessed regarding AI's capability and uses. Though it was still lagging, it is highly recommended that construction organisations strategically design policies for skills and competencies development [96]. However, construction students are rarely introduced to such advanced developed curricula [23,73]; hence, the literature emphasises the need for digital skills related to programming languages for future employment [22,135,136]. Such digital skills help implement digital technologies, optimising the construction process [18].

3.5.3. Design, Drafting, and Engineering

This category of digital skills encompasses the skills related to using CAD software, design-oriented software and other pioneering engineering material development. Knowledge and expertise in CAD and drawing software, such as AutoCAD and Revit, can be beneficial for construction personnel [5,22], such as field managers [99], to handle drawing-related complexities. Designing tools and software [101], leading to technical solutions, has also been deemed necessary in the construction industry [22]. Furthermore, engineering and designing modern materials, including nanomaterials and their relevant applications, support the building construction sector [100]. Such innovative and new construction materials help increase the sustainability and efficiency of the construction processes [137]. Possessing these skills has been linked with the digital literacy of civil engineering graduates and is the expectation of employers, such as in Indonesia [22].

3.5.4. Digital Data Acquisition and Integration

Today, numerous tools and devices are linked to IT, ICT and IoT systems, such as radio-frequency identification, smart sensors and wearables, which help in the data acquisition and communication of essential information amongst different systems [92,104,138–140]. These systems help develop integrated, intelligent, innovative systems such as smart homes and cities [141,142]. Furthermore, digital communication and collaboration are stressed in the literature [143], such as by the Russian builders [101], for effective digitalisation processes in construction projects. However, the integration of IT, IoT and relevant systems has faced barriers such as managers' lack of acceptability, limited skills, and lack of training and practical understanding [73,99,105]. It is further evident through the surveys conducted by past researchers [108,109], claiming that such skills are lacking among construction students and must be included in the curricula [106]. Hence, relevant digital skills such as IT skills [23,103], IoT skills [144], ICT skills [102], and skills related to the use of wearable technologies are deemed essential, leading to efficient safety monitoring [145] and better information circulation [107], organisational processes, and strategic planning [105].

3.5.5. Digital Literacy

Digital literacy is the knowledge and utilisation of digital devices for different tasks. The ongoing dynamic paradigm of digital technologies requires construction personnel to be digitally literate [101]; for example, field managers and personnel can interpret primavera schedules and Excel sheets [99]. Furthermore, digital literacy enables the stakeholders to use several computational tools and techniques, such as Microsoft Office in general and for resource calculation purposes, possessing an awareness of and essential knowledge to use state-of-the-art construction devices, technologies, and software [85,93,102–104,112].

Furthermore, the knowledge and competence of relevant essential technologies and tools can help in higher-end technological implementation towards Industry 4.0 [116], such as IoT in construction [105]. Construction employees' digital literacy enables effective and efficient management of the relevant technologies and projects in developing and developed countries [114,115,117]. The importance is evident as the relevant software and concepts, such as BIM [118] and MATLAB, solve practical civil engineering problems [111]. These are and shall be taught to construction-related students [113]. In addition, being digitally literate makes construction degree graduates eligible for prospective construction jobs [22,26,93,112].

3.5.6. Digitisation and Virtualisation

Due to the digitalisation trends, an enormous amount of data is produced during the project lifecycle. To collect, store, manage, map, analyse, and visualise such massive data, concepts and tools such as big data, blockchain, cloud computing and collaboration, data analytics, GIS, and laser and lidar scanning are utilised [18,22,23,31,103,146–149], benefitting several construction processes [97]. The utilisation and need for such digital competencies are evident from the relevant literature, emphasising the demand for digital skills in the future [5,18,23] for civil engineering and allied disciplines, aiding in the transition to Construction 4.0 [97].

3.5.7. Modelling and Simulation

A few of the most essential and popular digital skills required today are related to the use of BIM design, modelling and simulation, mixed reality (MR), AR, and VR due to their vast benefits [18,23,73,103,130,150]. Simulation and modelling have been helpful decision-support tools [131] for several construction project aspects [151]. BIM has been adopted in the construction industry for a long time and almost in all phases and types of projects [152], such as for safety management [57] and energy efficiency analysis [153]. BIM has helped establish new working platforms [5], developing and expanding the professional, managerial, and digital capacities [86,101,104]. However, enhanced and widespread adoption is still required for future jobs [22,119,120] because of the current barriers BIM is facing in its due adoption [21], such as in design creation and coordination, as-built-modelling, clash detection, and other project management tasks [128].

In connection with this, researchers are investigating the current skill level of students and professionals regarding BIM and their future training needs [23,103,118,121–124]. Moreover, after analysing the barriers, researchers have suggested implementation recommendations and strategies at the organisational and government level [125–127]. In addition, AR and VR have also been beneficial in educating personnel and preventing quality and safety issues [154]. Furthermore, AR and VR technological skills have proven highly effective in automated progress monitoring and safe working environments [73]. In addition, the digital twin concept has recently been established in the construction industry [155], aiding monitoring and facility management [156]. Although Construction 4.0 utilises the above-identified tools and technologies, the stakeholders are not ready for such an implementation [157]. The lack of relevant digital skills hinders their due implementation [18,158]. Strategies such as digital and cultural transformation and bridging the skills gap must be implemented to transition towards technologies such as BIM and digital twins [129].

3.5.8. Planning and Estimation

Innovative changes in the construction industry, such as in quantity surveying and construction management areas, are compelling the relevant construction industry professionals to possess modern skills to utilise tools, technologies, and software [104,159]. Productivity planning, scheduling and cost estimation, and optimisation via programming, technology, and software, e.g., Dynamo, Navisworks, Primavera, MS Project, and Vico schedule planners, are already happening in the industry and lead to productivity improvement [22,84,99,133,159–164]. However, efficient planning and estimation skills are not sufficiently developed among the graduates and must be effectively taught [23,118]. Currently, these are not aligned with what is expected from industry practitioners [165] to be able to work with modern and intelligent technological tools and devices [117].

It can be seen from the developed taxonomy [89], as presented in Table 2, that the enlisted digital skills relevant to the construction industry's needs are quite diverse. The research articles mainly focused on developing, using, or needing these individual skills, skipping an accumulative presentation of the needed skills. However, from the *co-occurrence network of keywords* (Figure 7) analysis, it is distinct that most of the foundational concepts and knowledge domains in the considered articles, such as [85,119,121–123], significantly lean towards BIM. These articles either focus on BIM skills and their development or BIM adoption and its barriers. Though this emphasises the importance of BIM skills and expertise, other digital skills are also gaining gradual significance in the academic and industry domains. Hence, as identified earlier in the literature, these skills must be effectively and collectively taught to future professionals.

The research for assessing the required digital skills is ongoing in all sectors, including construction and manufacturing, because technological change and upgrades are too fast. As discussed in the earlier sections, the digital skills of the construction industry need consolidation, and as a result, this taxonomy has been developed. Similarly, other sectors, such as the manufacturing industry, to which the construction industry is usually compared and contrasted, also have related developments. Though the manufacturing industry is more advanced than the construction industry, the taxonomy development of digital skills is progressive and evolving.

Several publications have presented the digital skills needed in the manufacturing sector. Per a report from Tulip [166], the essential digital skills required in the manufacturing industry include digital fluency, proficiency in writing and understanding code, competency in programming manufacturing-specific machines and devices, machining, fabrication, complex assembly, big data analytics, and robotics. Additional investigation indicates a growing significance of digital skills within the manufacturing industry. For example, Leitão et al. [167] underscore the significance of non-technical and technical digital skills across various manufacturing domains. Also, Azmat et al. [168] emphasise the necessity for workers to be equipped with digital skills in the age of industrial digitalisation. In addition, Akyazi et al. [169] created a skill database tailored for the manufacturing sector, encompassing anticipated future skill requisites for specific jobs.

Similarly, the researchers identified pivotal technical proficiencies and domain-specific knowledge requisite for data science and intelligent manufacturing roles. Likewise, Jurczuk and Florea [170] pinpointed deficiencies in digital skills in designing, implementing, and utilising solutions for automating and robotising business processes. They also developed a forward-looking framework for digital design competence to bridge these gaps. Florea [5], on the other hand, zeroes in on the imperative for educational institutions to align engineering education with the competencies essential to future factories. This analysis deduced potential competency requirements for *Factory of the Future* employees.

Furthermore, Salminen et al. [171] emphasised the imperative for industry and research providers to collaborate in bolstering technology management regarding skills and research. Moreover, Li et al. [172] assert that contemporary manufacturing professionals must undergo training in advanced, data-rich, computer-automated technologies. In the future, companies will require personnel possessing specialised skills in IoT-integrated additive manufacturing throughout the value stream. This encompasses proficiency in CAD, machine operation, raw material development, robotics, and supply chain management. These research works substantiate that digital skills are pivotal in the manufacturing industry's transition towards Industry 4.0, underscoring the urgency for skill enhancement and educational initiatives. However, it is crucial to note that while these skills represent excellence within Industry 4.0, they do not singularly constitute the comprehensive prerequisites of the manufacturing process [173].

Although there might be certain similarities between manufacturing and construction, significant distinctions exist concerning product complexity, safety risks, organisational structure, and the distinct nature of construction projects. Nonetheless, it is observed that the developed taxonomy of the construction industry in this research article and the skills presented by the manufacturing industry have some similarities and differences, mainly because the former is less digitalised. Because the manufacturing industry is already more digitalised, the relevant required digital skills are inclined towards robotics, code development, big data, automation technologies, CAD, additive manufacturing, and many more.

4. Conclusions

The construction industry has been relatively slow in adopting digital technologies compared to others, and one of the reasons for this is the lack of relevant skills and proper understanding. Therefore, the current study aimed to investigate the most currently used and needed digital skills in the construction industry. Initially, it followed the scientometric analysis methodology to evaluate the trends, outlets, co-authorship, and keyword co-occurrence networks in the published literature. The publication trend results implied that publishing in conference proceedings remained common in this area, but journal publications were also evident later. Scholars typically evaluate the reception of their new concepts at conferences, where they obtain early feedback before publishing in academic journals. Furthermore, conference publications can be advantageous for pioneering topics with minimal supporting literature, as they offer a valuable platform for discussing and disseminating original research findings.

Observing the diverse range of publication outlets dictates that various authors target multiple outlets to publish their research findings. The publication trends and outlet results provide insights to future researchers on where to publish their scholarship, possibly in journal outlets, to reach a broad audience and enhance the credibility and quality of their research. Researchers must select the most appropriate publication outlet for their research to ensure it reaches its intended audience and has the most significant impact.

Concerning the scientific collaboration network diagram, it is revealed that there is a lack of collaboration and networking in the studied research area. As a result, many have disregarded knowledge creation and dissemination through collaborative research. Therefore, there is a need for greater attention and effort to forming collaborative networks for future works. Furthermore, developing a collaborative network amongst different departments, universities, and countries would help identify the digital skills needed and utilisation around the globe. It could eventually lead to global need analysis and aid in systematically dealing with the skills shortage. Furthermore, the keyword co-occurrence analyses reveal that the concept of BIM is under the limelight despite the industry's need for several other skills. It is, therefore, recommended that scholars investigate different skills needs and development.

In the second phase of the research, the article mainly contributed to listing and categorising the most used and needed digital skills through a rigorous SLR process. The identified digital skills were organised into a taxonomy. These digital skills were categorised into automation and robotics, coding and programming, design, drafting and engineering, digital data acquisition and integration, digital literacy, digitisation and virtualisation, modelling and simulation, and planning and estimation. In contrast to past literature, which focused on specific skills investigation such as for BIM, IoT, ICT, and IT, or any specific job roles at the managerial and professional level, the shortlisting of the digital skills in this work was not specified to any job position. Instead, it included diverse digital skills ranging across professions. Therefore, the taxonomy could benefit many stakeholders, whether on-site or office-based staff.

5. Implications

The developed taxonomy contributes to practise as it would aid company-wide skills review of the existing staff base. This benchmarking will allow the companies to reevaluate and improve depending on their needs and strategic goals. The developed taxonomy can also be further assessed through a specific contextual point of view. As each country's construction industry technology adoption and digitalisation maturity level will be different, possibly there would be a difference in their digital skills need and utilisation. This warrants that the industry be assessed at national and international levels to identify the respective digital skills in demand. Such an analysis could help formulate future policies for the contextual construction industry. Also, the relevant institutes offering their services to train the concerned stakeholders must ensure that the contextual needs of digital skills are considered.

Additionally, such a taxonomy of digital skills becomes a foundation and the first point of contact for academia. It will help academia upgrade its existing infrastructure capabilities and technological and human capacity. Human resources can be re-skilled and up-skilled if they are not capable enough. Moreover, dedicating resources to education and training initiatives can be crucial to propel the industry into the digital age. By tackling these impediments to the digitalisation of the construction industry, the industry can significantly improve productivity, cut costs, and promote sustainability.

On the other hand, regarding the publishing domain and academic community, high-quality construction digitalisation journals can better serve the bodies of knowledge and practices by expanding their scope from using technology to improve the state of practice to teaching the relevant digital skills to improve human resources, who can then use the technology. Moreover, the existing construction education research-oriented journal outlets could also be targeted for relevant publications.

6. Limitations and Future Directions

Though the study has undergone a rigorous article collection and analysis process utilising SLR methodology, additional extensive content analysis methodology can also be employed for future works. It will help code and categorise the skills at deeper levels. In addition, more analyses can be conducted through VOSviewer, such as co-citation network analysis and bibliographic cluster analysis, to understand the bibliometric features further. Moreover, the keyword co-occurrence analyses reveal that the concept of BIM is in the limelight despite the industry's need for several other skills. The literature review inherently was mainly BIM-focused because of the popularity of BIM. Undoubtedly, several other skills are also linked to BIM's existence, usage, and dependency. However, it is recommended that scholars investigate different skills needs and development.

Based on the presented importance of the developed digital skills taxonomy, one of the critical future works that can be undertaken shall be based on each country's construction industry. It could help to ascertain the contextual needs of digital skills, and later, the global perspective could be established. This work is inherently evolving because of the underlying foundation of digitalisation and relevant digital technologies in demand and use. The ever-changing nature of technology adoption and the swiftly evolving landscape of Industry 4.0 could soon lead to some findings becoming obsolete. Dozens of relevant research works are being regularly published. Future works within this area shall be conducted at regular intervals to visualise the trendline of how the technologies are implemented and improving in AEC and what related digital skills are desired to remain updated and in competition.

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Appendix A

Table A1. Keywords Combinations and Relevant Search Results.

S. No	Keywords Combinations	Scopus Search Results	WoS Search Results
1	C DS	94	46
2	C DS D	13	6
3	C DS D E	2	0
4	C DS D E S	1	0
5	C DS D S	5	1
6	C DS D SLR	1	0
7	C DS D SLR E	1	0
8	C DS D SLR E S	1	0
9	C DS D SLR S	1	0
10	C DS D T	2	1
11	C DS D T S	1	0
12	C DS E	10	7

Table A1. *Cont.*

S. No	Keywords Combinations	Scopus Search Results	WoS Search Results
13	C DS E S	5	2
14	C DS S	21	12
15	C DS SLR	18	6
16	C DS SLR E	1	0
17	C DS SLR E S	1	0
18	C DS SLR S	2	1
19	C DS SLR T	5	3
20	C DS SLR T S	1	1
21	C DS T	23	17
22	C DS T E	4	4
23	C DS T E S	3	1
24	C DS T S	7	4
25	DS D E	3	2
26	DS D E S	2	1
27	DS D S	7	3
28	DS D SLR E	2	1
29	DS D SLR E S	2	0
30	DS D SLR S	2	1
31	DS D T S	1	0
32	DS E	12	10
33	DS E S	6	3
34	DS S	27	15
35	DS SLR E	2	1
36	DS SLR E S	2	0
37	DS SLR S	3	3
38	DS SLR T S	1	1
39	DS T E	5	5
40	DS T E S	3	1
41	DS T S	5	4

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