DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY

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DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY: A BIBLIOMETRIC REVIEW

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DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY: A BIBLIOMETRIC REVIEW

Abstract

Purpose- The construction industry has been traditionally referred to as slow when it comes to technological transformation. To investigate and present a scorecard of the construction industry in the last decade, the paper adopted Bibliometrics. The study identified the various digital transformation aspects in the construction industry and future research directions ~~are also identified~~.

Design/Methodology/Approach- To achieve the aim of this research, an inductive approach was adopted through a grounded theory strategy. Secondary data was retrieved from the Scopus database and analysed using Biblioshiny and VOSviewer. The data was retrieved through specific keywords related to the study focus.

Findings- The data analysis reveals that the construction industry has been active regarding the digital transformation drive in the last ten years. However, ~~there are countries that~~some countries are still lagging ~~in this regard,~~ ; the study identified and classified digital transformation in different countries accordingly. Digital transformation in the construction industry disrupts every aspect of the industry, albeit at different rates due to the existing barriers; hence the study identified areas that require further research. The study also proposed a balanced flow model for digital transformation discussion in the construction industry.

Limitations- The study adopted a single database for data collection.

Value- It is worthy of note that this is the first study that analyses the digital transformation in the construction industry in the last decade. The study maps the construction industry research efforts on digital transformation and provides an assessment of the construction industry in terms of digital transformation. It thus provides a theoretical and practical basis for researchers and practitioners alike.

Keywords: bibliometric, construction industry, digital transformation, industry 4.0, literature review, scientometrics, technological revolution

1 Introduction

The construction industry has been assessed to be a slow responder to technological advancement. Literature is replete with studies comparing the construction industry to other industries and concluding that the industry, unlike others, does not adopt and implement technologies swiftly(Castagnino, Rothballer, and Gerbert 2016). This aligns with (Fitzgerald et al. 2013) that lack of urgency is a major barrier to achieving digital transformation. This has led to a meagre productivity rate of the construction industry (WEF and BCG 2016), but this narrative seems to have changed recently. This can be attributed to the rapid industrial revolution in other sectors and the COVID-19 pandemic. These two cited reasons have a disruptive effect on the construction industry. Their impact has become a major driving force towards technological tools adoption in the construction industry.

Recently, there have been different studies on the adoption of various technologies in the construction industry. These technologies include but are not limited to RFID (Osunsanmi, Oke, and Aigbavboa 2018), robotics (Aghimien et al. 2019; Davila Delgado et al. 2019), Blockchain technology (Turk and Klinc 2017), BIM (Kassem et al. 2014; McGraw Hill 2014), IoT (Tang et al. 2019) and sensors (Kán et al. 2021). Mostly, the discussion has been on exploring the potentials of these individual technologies and their impact on the construction industry's productivity. There, therefore, exists a dearth in the holistic study of DT in the construction industry. In the light of these recent developments, this study aims to map the digital transformation efforts and aspects in the construction industry.

The importance of this study cannot be overemphasized, this study presents a one-stop, state of the art presentation of the digital transformation journey in the construction industry. This status will provide a critical analysis and provide a way forward in the digital transformation drive of the construction industry. Also, it provides a pathway for stakeholders in achieving comprehensive digital transformation of the industry. Therefore, librating the construction industry from the age-long stigma of lack of urgency in technological adoption.

2 Digital transformation (DT)

DT is highly disruptive; it disrupts markets considered to be highly regulated (Leong et al. 2017). To properly situate and understand the concept of DT; this study searched for the definition of digital transformation. This is important to establish the meaning and aspects of the concept. Extant literature was consulted to achieve this. All changes brought about by digital technology in all aspects of human life has been referred to as DT(Stolterman and Fors 2004). This definition puts forward the unrestricted disruption brought by DT. It can be said that DT thus changes everything about human living and the conduct of everyday business. This is unsurprising as the human plays different roles in the social network in relation to DT. ~~(~~Westerman et al. (2011) define~~s~~ DT as the employment of technology in order to radically improve the performance of enterprises. This definition emphasises the radicality and improvement that comes with DT, especially for business enterprises~~.~~.

Consequently, no sector or organisation has been shown to be immune to the effects of DT (Hess et al. 2016). ~~Furjan et al. (~~Furjan, ~~Tomičić-Pupek, and Pihir~~et al. (2020) describe it as a "digital technology-based improvement" to the business process. ~~(~~Matt~~, Hess, and Benlian~~et al. (2015) describe~~s~~ DT *as "a continuous complex undertaking that can substantially shape a company and its operations*". ~~Mahraz et al. (~~Mahraz, ~~Benabbou, and Berrado~~et al. (2019) describe DT as a disruptive change process. Using the works of (Akmajian et al. 2001; ~~R.~~ Suddaby 2010; Wacker 2004), ~~(~~Vial (2019) was able to construct a conceptual definition for DT. According to (Vial 2019), DT is *"a process that aims to improve an entity by triggering significant changes to its* *properties through combinations of information, computing, communication, and connectivity technologies".* This definition refers to DT as a process that achieves measurable changes through ICCCT. Construction DT involves the significant, disruptive change to construction processes (vertically, horizontally and longitudinally) for improving construction output and productivity to achieve project outcome and better client satisfaction through the adoption of information, computing, communication, and connectivity technologies.

To achieve DT, different drivers have been identified in literature. ~~Nadkarni and Prügl (~~Nadkarni and Prügl (2020) classified these drivers into two: technology and actor. Meanwhile, ~~(~~Hrustek, et al.~~Tomicic-Furjan, and Pihir~~ (2019) classified it into customer, technology and organisational development drivers. ~~(~~Verhoef et al.(2021) adopted three drivers for their study, which are: Digital Technology, Digital Competition and Digital Customer Behavior. From the identified drivers, it is evident that technology is not the only ingredient to achieving DT. Hence it is wrong for sectors to focus on the technologies required without consideration for other drivers required for DT.

~~Table 1: Challenges, benefits and some identified DT technologies.~~

Table 1: Challenges, benefits and some identified DT technologies.

	Reference	Challenges
Challenges	(Fitzgerald et al. 2013)(Westerman et al. 2011)(Yucel 2018)	Lack of impetus, Regulation and reputation, Unclear business case, Missing skills, Culture issues, IT Difficulties, Governance challenges, lack of urgency, Not enough funding, Limitations of IT systems, Roles and responsibilities are not clear, Lack of vision, Unclear business case, Business units implementing independently in silos, Culture not amenable to change, Lack of leadership skill, Regulatory concerns, strategy related, support and sponsorship-related, implementation-related
Benefits	(Fitzgerald et al. 2013)(Hess et al. 2016)(Capuşneănu et al. 2021)(Westerman, Bonnet, and Mcafee 2014)(Schwertner 2017)	productivity improvements, cost reductions and innovation, better customer experiences and engagement, streamlined operations and new lines of business or business models, organisational efficiency, organisational agility, manufacturing innovation, product quality and safety and process improvement, streamline workflow and improve productivity
Keywords	(Mahraz et al.	Industry 4.0, Digital business enterprise architecture,

employed in DT research	2019; Nadkarni and Prügl 2020; Reis et al. 2018)	digital transformation, digitisation, IoT, internet, Innovation, technology, digitalisation
Identified technologies		Big Data Analytics, IoT, cloud computing, blockchain, big data, mobile technology, 3D printing

Achieving DT is requires change by firm, processes and the ecosystem. Old firms are required to embrace new organisational structures and processes in order to blend with the DT trend(Sebastian et al. 2017). Furthermore, they must adopt the technologies suited for the transformation in their line of work. Although it has been established that adopting all technologies is not the prerequisite for DT. DT can be attained without necessarily adopting all the technologies (Yucel 2018).~~ Verhoef *et al*~~. ~~(~~Verhoef et al. (2021) presented a flow model for discussion of DT, which hints at the different aspects of DT (Figure 1). Transiting from the status quo and achieving DT, organisations will have to overcome hurdles. Table 1 presents a list of hurdles, benefits and technologies for achieving DT.

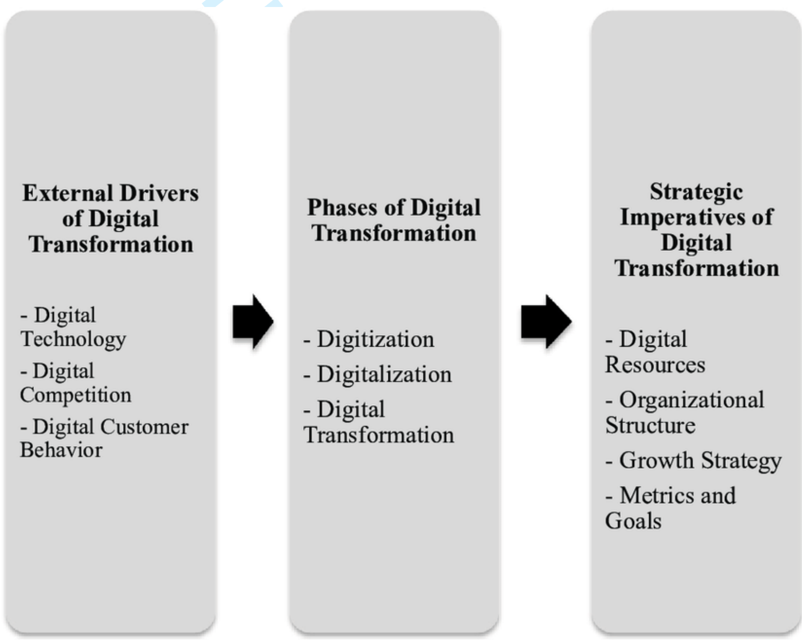

Figure 1: Flow model on DT discussion (Verhoef et al. 2021)

3 Summary and gap

A critical analysis of the works on DT reveals that, although it involves changes made possible by technology but it is not just about the technologies. It also affects every aspect of human endeavours. It can also be inferred that it is a disruptive yet continuous process. It is, therefore, the aim of this paper to map the completeness of the DT drives in the construction industry. With this study, the following objectives are to be achieved: (1) Conduct a literature analysis using themes of the digital transformation of the construction industry, (2) To articulate the technologies adopted in the construction industry towards achieving DT and (3) To identify the research frontiers, hot topics and future trends. ~~based on the other drivers identified, this study will critically analyse the DT drivers peculiar to the construction industry.~~ This study is important to the industry and its drive to achieve DT. It also provides practitioners with an insight into the state of the industry and what is required.

4 Research methodology

This study aims to articulate the progress made in achieving DT of the construction industry research. Bibliometrics was chosen to achieve this because this method is used to primarily answer three questions, which are outlined below(Aria and Cuccurullo 2017): (i) identify the knowledge base of a research field and the intellectual structure; (ii) examine the research front (or conceptual structure) of the research field; (iii) produce a social network structure of a particular scientific community

Through this methodology (illustrated in figure 2), the study achieved the following: (i) the most cited documents; (ii) the most productive and consistent authors; (iii) the trend words; (iii) DT drivers and aspects in the construction industry. The research methodology for this study is discussed under five headings based on the standard workflow for bibliometric mapping (Zupic and Cater 2015). These five headings are study design, data collection, data analysis, data visualisation and interpretation.

4.1 *Study design*

Study design entails the definition of the study research questions and making the choice of appropriate methods to achieve it(Aria and Cuccurullo 2017). Other decisions made at this stage include the timespan, keywords, selection of the database, the software for data analysis, among others, to achieve the study objective.

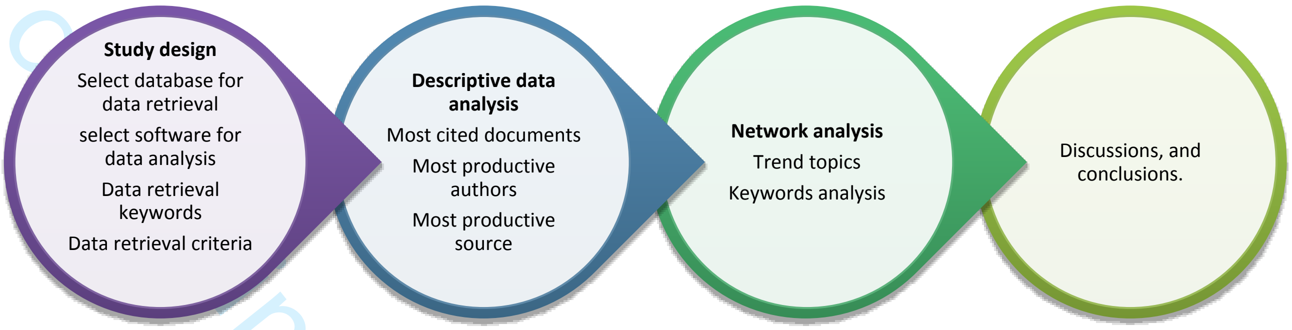

Figure 2: Study research design

4.2 *Data collection*

To achieve data collection for this study, the Scopus database was adopted. Literature has established that there are other databases like PubMed, Web of Science and Google Scholar, and these databases have peculiarities (Falagas et al. 2008; Harzing and Alakangas 2015; Martín-Martín et al. 2018). The Scopus database was chosen for this study because it is considered more comprehensive(Mongeon and Paul-Hus 2016) and has been adopted by various studies for bibliometric review (Jin et al. 2019; Newman et al. 2020). Furthermore, the Scopus database presents the widest pool of digital peer-reviewed publications(Newman et al. 2020). It thus provides an extensive and up to date relevant database for the present study on digital transformation. The search for publications was based on keywords. These keywords are either found in the title, abstract or keywords of publications. The documents retrieved are based on those having the selected keywords. For this study, the keywords adopted is ("construction industry" AND "technology" OR "Innovation" OR "industrial revolution" OR "Digitisation"). Appendix 1 provides the search string for the study.

To properly focus the data retrieved for the study, the study adopted a time frame of 2010-2020. This is in order to map the recent advancements effectively in the construction industry towards achieving DT. In line with achieving currency of data, the study adopted only journal articles. Thus, other types of publications were excluded (i.e. conference proceedings, books, book chapters, among others). Journal articles are considered to publish current research findings and efforts and are also believed to be more rigorous and detailed when compared to conference proceedings. Extant literature has also adopted using only journals for similar studies (Jin et al.

2018; Ramos-Rodrígue and Ruíz-Navarro 2004; Zheng et al. 2016). Another reason for settling for journal articles was because most conferences were affected by the Coronavirus pandemic; hence many were postponed and some cancelled. Search output was further pruned by applying the subject area criteria by restricting publications only to the engineering field. A total of 1892 articles were returned and considered by this study from the initial 11,428 documents returned before the screening.

4.3 *Data analysis*

Although there are numerous software to analyse bibliometric data as chronicled by (Cobo et al. 2011; Moral-Muñoz et al. 2020), however, in order to fully retrieve all information from the rich data collected, this study analysed its data using Biblioshiny and VOSviewer. These two software have been adopted for data analysis in literature; however, a combination of the two is not commonplace. Biblioshiny was adopted majorly for the descriptive analysis, while the visualisation was achieved using VOSviewer.

Biblioshiny is a version of Bibliometrix for non-coders. It is powered by Bibliometrix (Aria and Cuccurullo 2017); however, Biblioshiny is web-based. It works with Scopus, Web of Science, Dimensions, Pubmed and Cochrane library. Biblioshiny was chosen for the descriptive data analysis. It possesses a well organised and intuitive interface (Moral-Muñoz et al. 2020).

VOSviewer (van Eck and Waltman 2019; Jan van Eck and Waltman 2006) is primarily a visualisation software. It is employed for creating maps based on the data. Networks primarily contain items and links. Items are the objects being studied, while links show the relations between two items (van Eck and Waltman 2019). Links connect two items. VOSviewer has been used for bibliometric study in similar studies in the digital transformation era; for instance, (Aghimien et al. 2019, 2020, 2021; Chellappa, Srivastava, and Salve 2021; Safura Zabidin et al. 2020) employed it in mapping industry 4.0 in the construction industry and digitalisation studies, workers health and safety, computational modelling respectively. ~~Visulaisation~~ Visualisation has been popularly adopted in ~~vatious~~ various construction industry research domains (Babalola et al. 2021; Mariam, Olalusi, and Haupt 2020).

5 Interpretations and discussions

5.1 *Progression of publications*

Considering the laid back nature of the construction industry in terms of digital transformation, it is essential to investigate the research outputs in this space. This output is an indication of researchers efforts in achieving DT in the construction industry. Figure 2 shows the details of the research outputs from 2010-2020. From the figure, there is an upward increase in the DT research output in the construction industry. Aside from 2011 and 2014, where the outputs dipped, consequent years have experienced a steady upward trend. This is an indicator that the construction industry is steadily making conscious efforts to achieve DT.

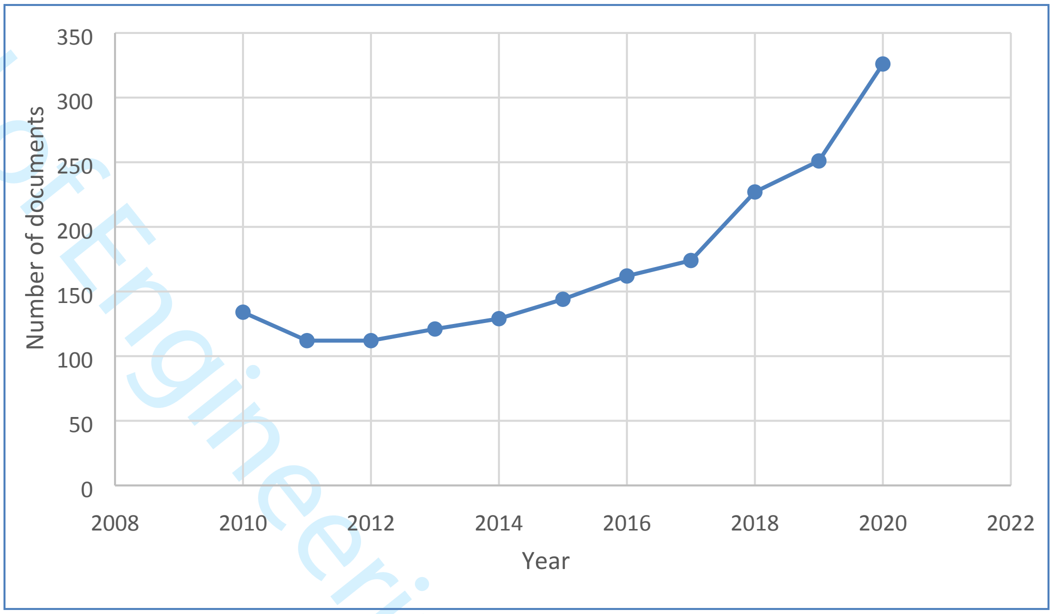

Figure 3: Construction DT publication output between 2010-2020

5.2 *Geographical DT research efforts*

To identify the knowledge contribution on a geographical basis, the global contribution of various countries was analysed. Figure 1 presents the frequency of these countries. China leads with 497 documents, followed by the USA with 481 documents.

Table 1 presents a classification of countries adopted by this study based on the number of documents contributed by these countries. Countries with more than 100 documents were classified as DT leaders, and DT contemplators were those countries with documents lesser than 100 but greater than 50. Furthermore, DT strugglers and DT Laggards were terms used to describe countries with less than 50 documents but more than ten and less than ten, respectively.

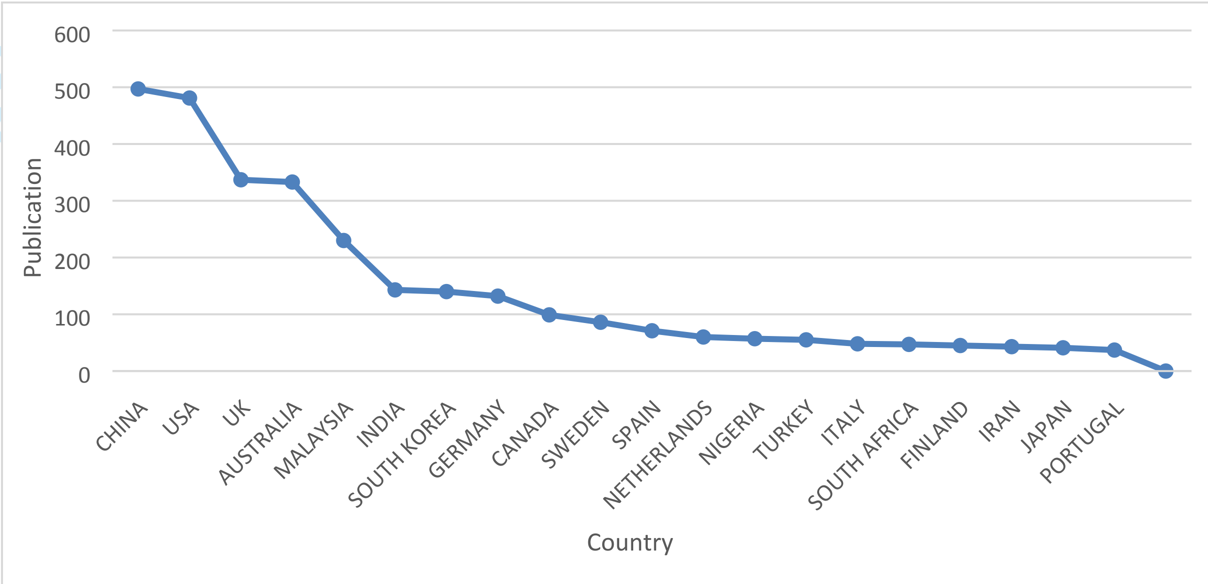

Figure 4: Geographical publication statistics

A critical analysis of Table 21 reveals that most countries that were referred to as BIM leaders are also DT leaders. According to (Edirisinghe and London (2015), the USA, UK, South Korea, and Australia were referred to as BIM leaders. Other BIM leaders, according to (Edirisinghe and London 2015), are Hong Kong, Singapore, Norway and Finland.

Table 2: Classification of countries based on publication

Classification	Countries	Nr of documents
DT leaders	China, USA, UK, Australia, Malaysia, India, South Korea, Germany	Greater than 100
DT contemplators	Canada, Sweden, Spain, Netherlands, Nigeria, Turkey	Greater than 50
DT strugglers	Italy, South Africa, Finland, Iran, Japan, Portugal, France, Pakistan, Israel, Czech Republic, Jordan, Slovakia, Slovenia	Less than 50
DT laggards	Ireland, Indonesia, Iraq, Sri Lanka, Qatar, Cyprus, Argentina, Bangladesh, Colombia, Ethiopia, Greece, Kazakhstan, Kenya, Lebanon, Mexico, Morroco, Oman, Serbia, Ukraine, Yemen, Hungary, Kuwait, Uzbekistan, Croatia, Latvia, Philippines, Romania, Bulgaria, Cameroon, Iceland, Kyrgyzstan, Liberia, Luxembourg, Macedonia, Mozambique, Peru, Rwanda.	Less than 10

Although the latter four are not DT leaders, however, others are. This brings about the question of if the digital divide is never going to be closed up. Also, it gives credence to the Matthew effect summarised simply as the rich getting richer and the poor getting poorer. Although (Van Dijk and Hacker 2003) posits that early adopters bear the most burden of implementation as they pay for innovation, thereby making it cheaper for late adopters. The question with this position as it affects the construction industry is if the innovation is subsidized enough for late adopters. If late adopters can adopt it, most times while late adopters are still struggling to adopt the last, there is a new innovation or an upgrade. This mostly puts the late adopters in a difficult position of catching up and closing the digital divide.

5.3 *Influential publications*

This section discusses the most cited documents or publications in the construction DT space in the last decade. Citations have recently been used to determine author influence in bibliometric studies (Saka and Chan 2019; Wang et al. 2020). Table 3~~2~~ presents the top 20 most cited construction DT publications. ~~(~~Zabalza Bribián, Valero Capilla, and Aranda Usón (2011)'s work remains the most cited. The normalized total citation column makes it possible for the benchmarking and comparison of documents. A critical look at the table suggests that BIM, 3D printing, VR/AR are some of the technologies focused on by the studies. However, BIM appears to be the most talked-about technology in the last decade in the construction industry. It can be inferred that BIM has enjoyed concerted attention from the industry. Furthermore, this might be inferred to mean that many construction industry stakeholders have a strong belief in BIM to change the status quo in the construction industry (Eastman et al. 2008).

5.4 *Influential Journals*

To establish the relevant and influential journal sources in the construction DT space, this study adopted the Bradford Law of 1934 and observed publication source growth (using Loess smoothing) in the subject area. Figure 4 and Figure 5 respectively present the graphical representation of these two approaches. Figure 6 presents the source growth trend of the publication sources.

Bradford's Law was formulated by a British mathematician, documentationalist and Librarian, Samuel C. Bradford (Jeremy Norman 1934). This law posits that in any given research space, there exist different classifications of sources. Bradford went further to categorise the sources into productive core sources, moderate producers and those constantly diminishing. Hence the first classification or zones are the most cited in the research field; the second zone enjoy average citations while the

Table 3: Most cited construction DT documents

~~Paper~~Reference	Source	~~DOI~~Publication title	Total Citations	TC per Year	Normalized TC
~~(~~Zabalza Bribián et al. (2011)	Building and Environment	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential	621	56.45	19.1551
~~(~~Gu and London (2010)	Automation in Construction	Understanding and facilitating BIM adoption in the AEC industry	444	37	12.4105
~~(~~Singh, Gu, and Wang (2011)	Automation in Construction	A theoretical framework of a BIM-based multi-disciplinary collaboration platform	333	30.27	10.2716
~~(~~Bos et al. (2016)	Virtual and Physical Prototyping	Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing	316	52.67	17.2771
~~(~~Sacks, Koskela, and Dave (2010)	Journal of Construction Engineering and Management	The Interaction of Lean and Building Information Modeling in Construction	301	25.08	8.4134
~~(~~Arayici et al. (2011)	Automation in Construction	Technology adoption in the BIM implementation for lean architectural practice	277	25.18	8.5442
~~(~~Häkkinen and Belloni (2011)	Building research and information	Barriers and drivers for sustainable building	270	24.55	8.3283
~~(~~Teizer et al. (2010)	Automation in Construction	Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system	269	22.42	7.519
~~(~~Pomianowski, Heiselberg, and Zhang (2013)	Energy and Buildings	Review of thermal energy storage technologies based on PCM application in buildings	267	29.67	10.5821
~~(~~Qi et al. (2010)	Journal of Cleaner Production	The drivers for contractors' green innovation: an industry perspective	231	19.25	6.4568
~~(~~Miettinen and Paavola (2014)	Automation in Construction	Beyond the BIM utopia: Approaches to the development and implementation of building information modeling	208	26	10.7157
~~(~~Leung et al. (2015)	Materials and Structures	Review: optical fiber sensors for civil engineering applications	199	28.43	9.7969
~~(X.~~ Li et al. (2018)	Automation in Construction	A critical review of virtual and augmented reality (VR/AR) applications in construction safety	185	46.25	13.5163
~~(~~Cheng and	Automation in Construction	Real-time resource location data collection and visualization technology for	185	20.56	7.3321

Teizer (2013)		construction safety and activity monitoring applications			
(Dossick and Neff (2009)	Journal of Construction Engineering & Management	Organizational divisions in BIM-enabled commercial construction	177	14.75	4.9474
(Becerik-Gerber and Rice (2010)	Journal of Information Technology in Construction	The perceived value of building information modeling in the U.S. building industry	171	14.25	4.7797
(Pauwels and Terkaj (2016)	Automation in Construction	EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology	157	26.17	8.5839
(Eastman et al. (2010)	Journal of Computing in Civil Engineering	Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards	152	12.67	4.2486
(Pauwels et al. (2011)	Automation in Construction	A semantic rule checking environment for building performance checking	142	12.91	4.3801
(Li et al. (2015)	Safety Science	Proactive behavior-based safety management for construction safety improvement	141	20.14	6.9415

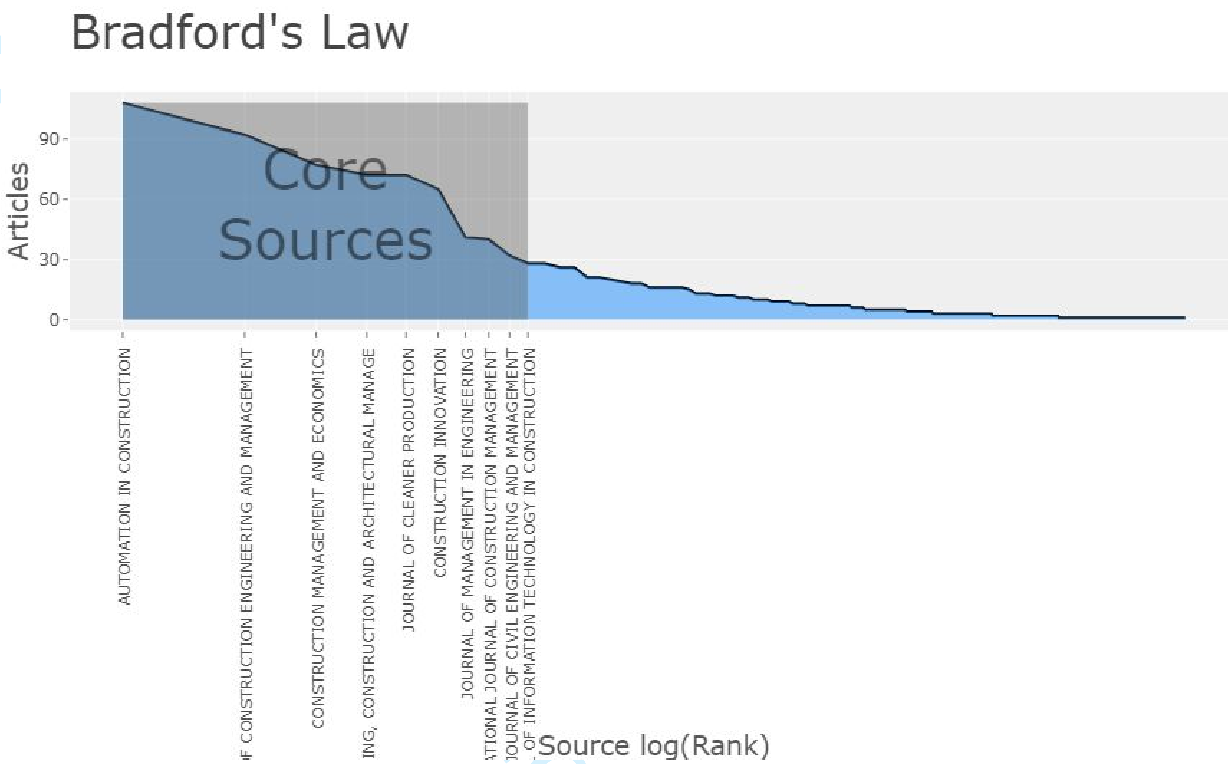

Figure 5: Core sources in construction DT

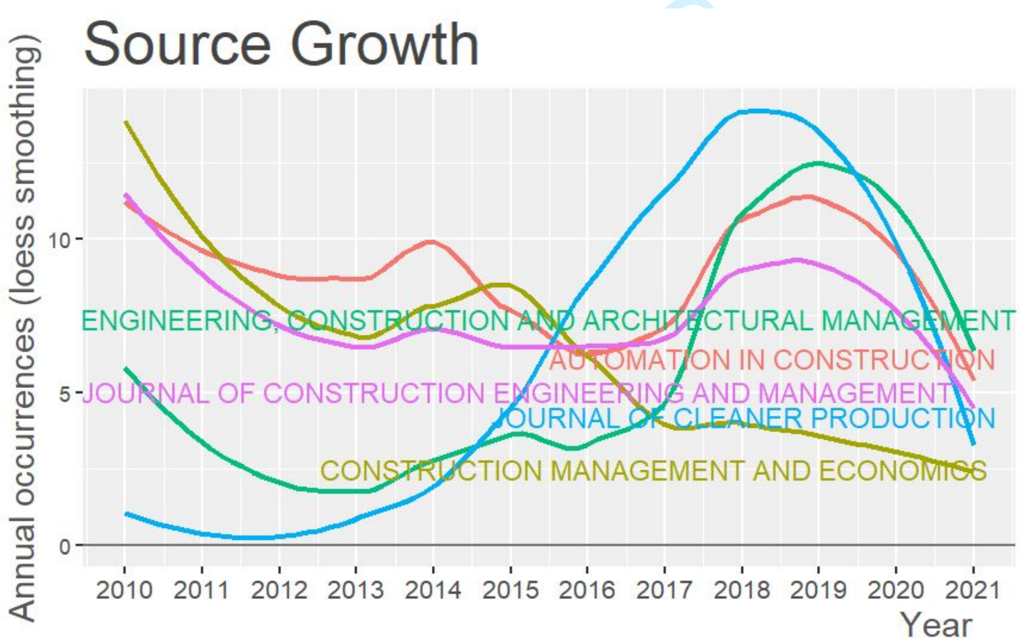

Figure 6: Annual source growth trend

third are seldomly cited respectively. In this order, this is employed to make reference to the importance attached to these sources. This law has been used for library stocking decisions and literature search decisions the world over [73]–[76]. The core sources of DT research is led by Automation in construction. The second core source is Construction Engineering and Management.

A study of the growth of these sources in DT research reveals that the Journal of cleaner production has experienced a strong upward growth more than other sources. This is followed by Engineering, Construction and Architectural management. However, this cannot be said of Construction management and economics, as it has experienced a steady annual decline.

5.5 Author outputs

Aside from the influences commanded by authors through the citations, it is also essential to articulate the top authors in terms of publications. This was similarly adopted by (Aghimien et al. (2021). Figure 76 presents a trend of top-producing authors over the years. The top five producing authors are LI, H. with 21 publications, SKITMORE, M. with 19 documents, LIU, C. and TEIZER, J. having 13 publications each, and CHAN, A.P.C. contributing

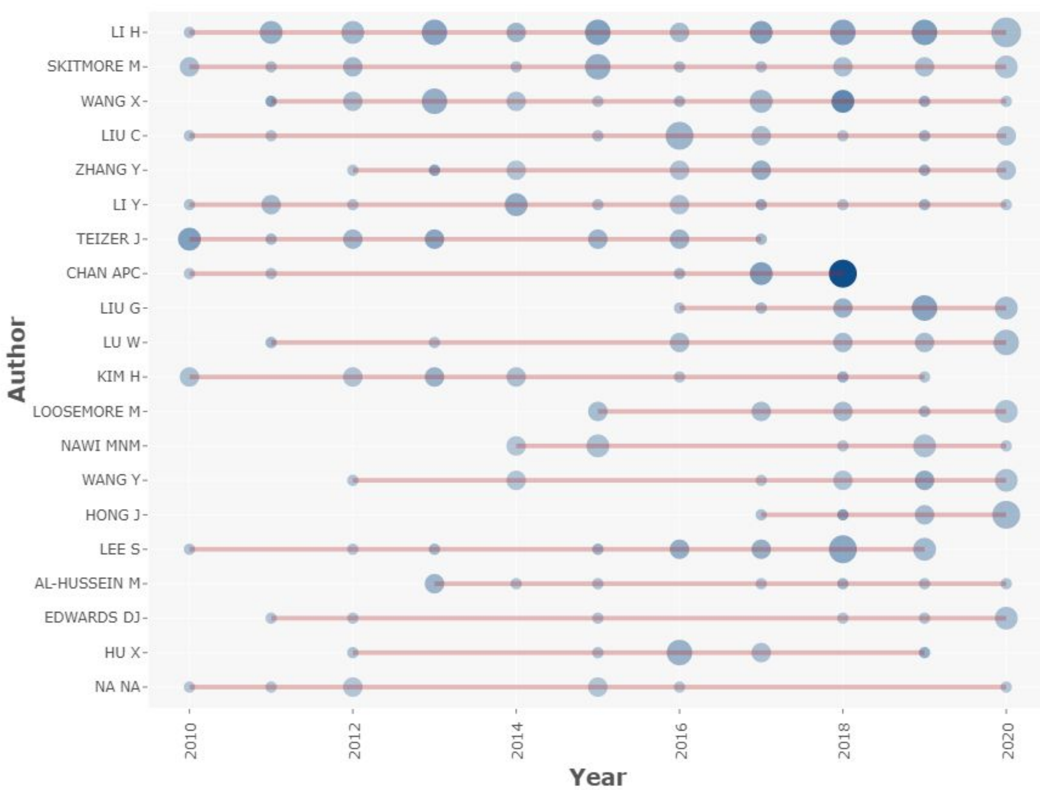

Figure 7: Top authors production over time

11 articles. Figure 76 presents the production trends and consistency of the authors. : LI, H. appears to be the most consistent authors over the years, followed by SKITMORE, M and LI, Y.

6 Network analysis and trend word analysis.

6.1 *DT trend topics*

This refers to topics or areas of focus in construction DT. This section identifies these words and the year they became a topic of interest in the construction industry. These topics become popular as many researchers publish to understand and apply them to the construction industry. Figure 8 ~~7~~ and Table 4~~3~~ presents these DT related keywords against the year and frequency of occurrence in the construction DT research.

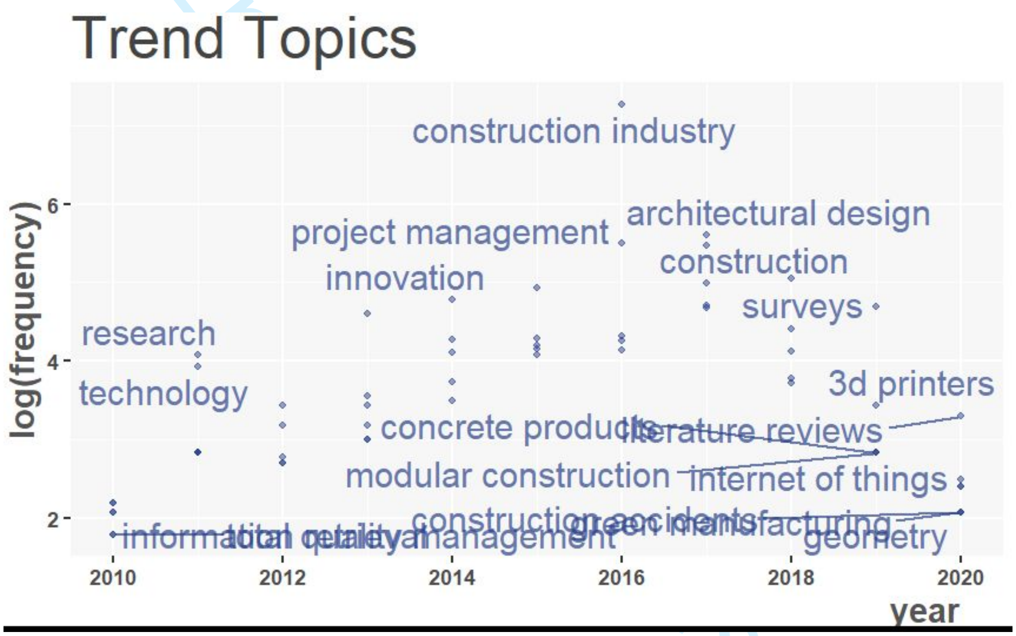

Figure 8: Construction DT trend topics

Table 4: DT trend words

Item	Freq	Year	Item	Freq	Year
Building information modelling	9	2010	Information and communication technologies	42	2014
New technologies	8	2010	Energy utilization	63	2016
Technological forecasting	8	2010	Sustainable development	148	2017
Technology	51	2011	Building information modelling	82	2018
Three dimensional	17	2011	Internet of things	17	2019
Computer simulation	16	2012	Modular construction	17	2019
Information technology	100	2013	3d printers	31	2019
Radio frequency identification (rfid)	31	2013	Industry 4.0	12	2020
Information systems	24	2013	Learning systems	11	2020
Innovation	120	2014	Green manufacturing	8	2020

The industry has been discussing sustainable development more, followed by innovation and information technology. The next section is the network analysis of co-occurring words to understand the research directions and map out the clusters. Also, it provides an insight into when these technologies and concepts were introduced into the construction industry research discussions. For instance, BIM was introduced in the year 2010, RFID in the year 2013, among others.

6.2 *Research interests in construction DT.*

This section discusses the different research focuses in construction DT. To achieve this, the study analysed the co-occurrence of keywords (authors and journal indexed) from the data collected using VOS viewer. This approach provides a more balanced and comprehensive pool of keywords than the adoption of authors keywords or journal indexed keywords individually. The study adopted a minimum occurrence of 5 for the keywords; this produced a total link strength of 68436, 6 clusters and a total of 793 keywords. These keywords were clustered through association hence we have 6 clusters. The clusters are consequently named and discussed in light of the different aspects of DT as identified in (Verhoef et al. 2021). Figure 9 presents the co-occurrence map, and the list of keywords in each cluster are presented in the appendix.

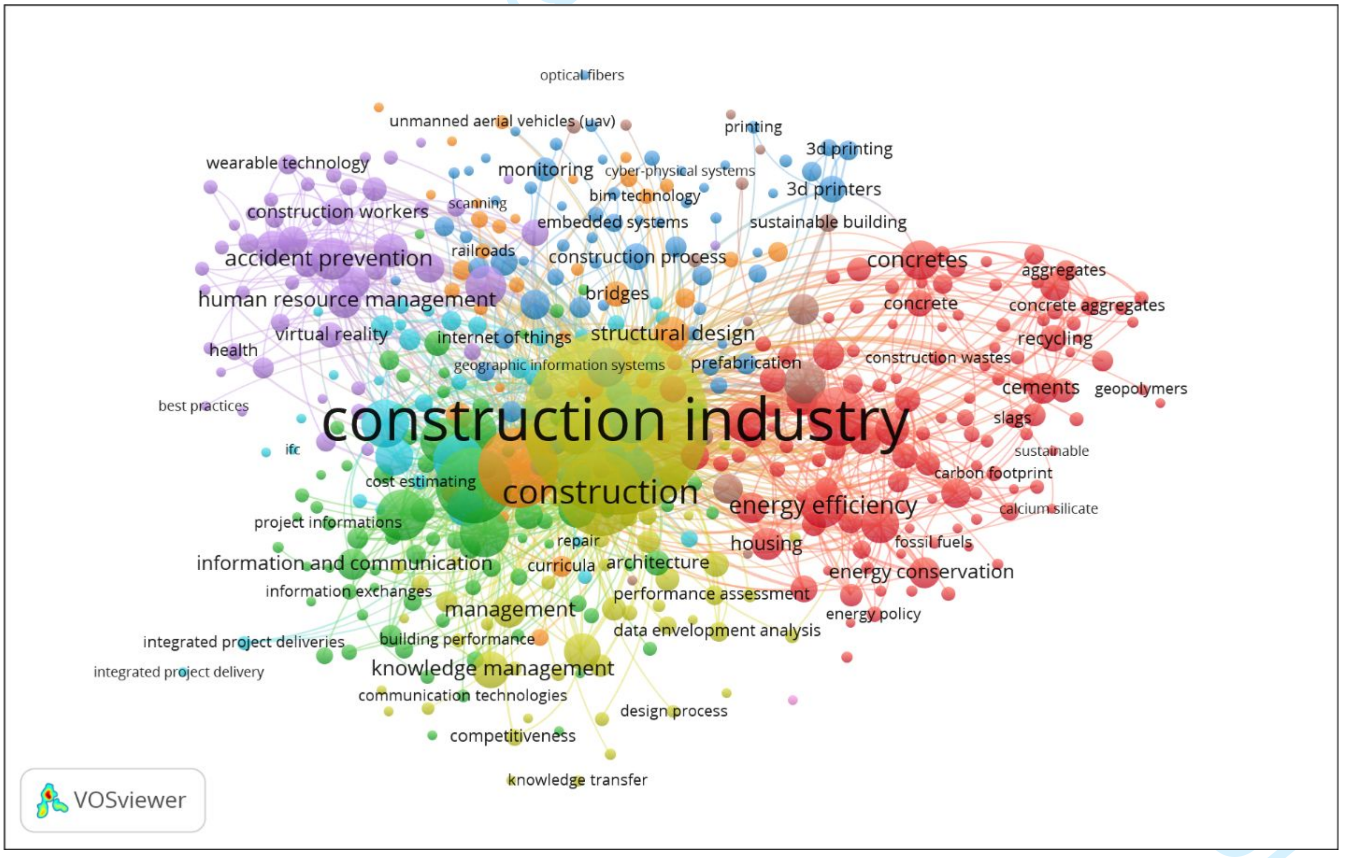

Figure 9: Research focus network visualisation

Cluster 1 **(Organisational change management)**

This cluster (red region) can be said to be the organisational change management and challenges faced by construction organisations due to the introduction of technologies. The cluster also identifies three aspects of DT, which are technology, organisational behaviour and construction project aspects. The technologies in the cluster are blockchain, green building technologies, cloud computing and ICT. The technologies disrupt the way things are done in organisations and on projects. For instance, blockchain technology is a decentralised system for making transactions hence remove unnecessary bottlenecks and intermediaries. Adopting blockchain technology in the construction industry ensures a more open process and increases confidence among the project parties. According to (Kassem, Lia, and Greenwood 2018), it reduces human error, makes traceability of transactions possible. Blockchain technology can be applied in BIM, intelligent transport, smart cities (Kassem et al. 2018), construction supply chain (Wang *et al.*, 2017). DT as an external force causes structural changes in organisations and informs survival strategies (Cameron and Green 2009; Matt et al. 2015). Some strategies identified are inter-firm collaborations to help construction organisations survive the disruptive effects of DT.

Furthermore, DT enables dynamic capabilities in organisations and ensures competitive advantages(Teece 2018; Teece, Pisano, and Shuen 1997). From the preceding, the three aspects in this cluster affect the final project outcome. Although it disrupts the existing system and workflow, it, however, adds value to the construction industry. Summarily, it can be said that these technologies bring organisational change management, affect organisational structure and cultures. It also makes organisations develop strategies for survival in the digital-driven world and consequently affects all construction stakeholders, affects the supply chain and improves the project management process.

Cluster 2 **(Technology, project and sustainability)**

Although concrete is widely used in construction, it has been observed that despite its advantages, it is laden with several challenges, among which is the contribution to the global CO_2 output, labour intensive, health implications for workers (Bos et al. 2016) among others. Cluster 2 (lime green) addresses the technology, project and sustainability aspects of DT. The technology identified in this cluster is additive technology which 3D printing is one of the methods. 3D printing has been in use in the construction of concrete since the mid-1990s and possesses the potential to address the challenges of the traditional concrete production method(Bos et al. 2016). Some of the inherent benefits in additive manufacturing for the construction industry include reduction of construction material waste (Hossain et al. 2020), use of multiple materials (Delgado Camacho et al. 2018) which will encourage the optimal use of materials, and also provide design freedom and encourage automation of the construction process (Paolini, Kollmannsberger, and Rank 2019). 3D printing in construction also possesses the advantage of solving the labor shortage being experienced in the construction industry in some parts of the globe(Hossain et al. 2020). Despite the identified benefits of 3D printing in the construction industry, its large scale adoption has been hampered by the huge infrastructural costs (Hossain et al. 2020) required by stakeholders.

Cluster 3 **(technology, data exchange and application)**

The colour green indicates this cluster on the network visualisation. The three classifications of keywords are technology, data exchange and application aspects. The technology in this cluster is BIM and CAD. The other aspects are data management and sharing and the applications of BIM in the construction industry. BIM has been described as a revolutionary technology in the construction industry and it is used in conjunction with other technologies to achieve many benefits for the construction industry. ~~Ge *et al.* (~~Ge et al. (2017) through a case study demonstrated that BIM provides accurate estimations of deconstruction materials and improves waste management. Thus it is useful in every aspect of the building lifecycle from planning to demolition. The widespread adoption of BIM especially in developing countries, has been observed to suffer set-backs due to some barriers – cultural, educational, infrastructural, policy and transparency(Adekunle, Aigbavboa, and Ejohwomu 2020). However, the developing countries ~~has~~ have been achieving good adoption rates recently despite the hurdles (Adekunle, Ejohwomu, and Aigbavboa 2021). Thus it can be inferred that despite the study of Jung and Lee (Jung and Lee 2015) indicating a wide difference in the adoption rates across continents, this has changed. Although the present adoption rate across continents, developed and developing countries is lacking.

Cluster 4 **(artificial intelligence, big data, virtual reality and wearable technology)**

This is shaded in yellow on the network visualisation. This cluster, unlike the previous ones, has only two aspects which are technology and applications. The technology identified in this cluster are artificial intelligence, big data, virtual reality and wearable technology. Wearable technologies in the construction industry include smart vests and wristbands (Choi, Hwang, and Lee 2017). The application identified in this cluster is mainly on construction health and safety. The adoption of virtual reality and wearable technologies has been shown to prevent accidents, promote and improve construction safety (AL-Sahar, Przegalińska, and Krzemiński 2021; Frank Moore and Gheisari 2019; Zhao and Lucas 2015). Connectivity has been identified as a barrier to the adoption of big data applications in the construction industry (Hedges 2012). In order to aid the adoption of Big data, (Martínez et al. 2021) developed and validated models necessary for the easy adoption of big data. The developed model identified, described and established the relationships between the elements of the model architecture. Similarly, ~~Bilal et al (~~Bilal et al. (2016) proposed a big data ~~arichiteture~~ architecture for construction waste analytics. Exploring big data in the construction industry presents a process improvement goldmine. This is due to the huge data generating nature of the construction industry.

Cluster 5 **(Internet of things (IoT) and Cyber-physical systems (CPS) and construction project)**

The colour purple indicates this cluster. The cluster has three aspects, namely, technology, benefits and construction project aspects. The technology identified in this cluster are the Internet of things (IoT) and Cyber-physical systems (CPS). IoT as a standalone technology or when used in combination with other emerging technologies in the construction industry, enhances construction productivity (Heiskanen 2017) in prefabrication~~,~~ and modular construction (C. Z. Li et al. 2018; Zhao, Liu, and Mbachu 2019; Zhong et al. 2017) and CPS employed for real-time monitoring (Liu et al. 2020). These technologies, through their various uses, enhance productivity and ensure quality assurance. These technologies are also integrated with BIM to achieve better process improvement and efficiency. For instance, building information modelling and Intern~~a~~et of things (Tang et al. 2019).

Cluster 6 (underground construction and technology)

This cluster is indicated in blue colour. This cluster contains three aspects which are technology, construction projects and application aspects. However, the application identified in this cluster is for underground construction; this includes the construction of passageways, tunnels among others, underground. Laser scanning is a useful and potent tool for ~~the construction and maintenance management of~~constructing and maintaining tunnels(Wang et al. 2014). Other technologies in this cluster are RFID, robotics, wireless sensor networks, and unmanned aerial systems. These technologies are useful for different stages of the construction project, from planning and design, construction, commission and operation and commission. The uses include information management and traceability, 3D printing, prefabrication of building components, aerial survey and progress monitoring, safety inspection, building maintenance (Davila Delgado et al. 2019; Lu, Huang, and Li 2011; Martinez et al. 2021; Tatum and Liu 2017; Zhou and Gheisari 2018).

A critical study of the clusters mentioned above gleaned from the bibliometric data suggests that the DT discussion in the construction industry goes beyond the proposed scope (Verhoef et al. 2021). Hence the study ~~comes up with~~developed a flow model (Figure 10) for DT discussion in the construction industry.

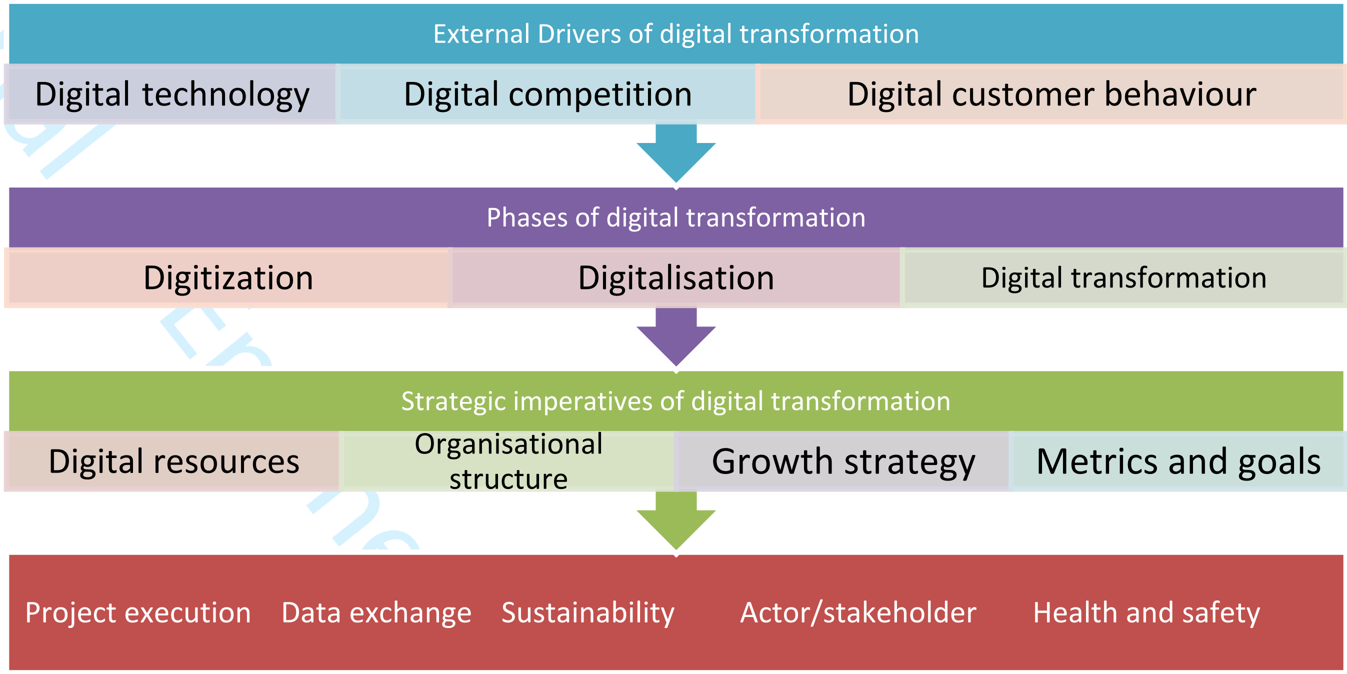

Figure 10: Flow model for construction DT

The DT in the construction industry spans organisational, project, stakeholder and the environment.

7 Future directions and trends for DT in construction

The section discusses the future trends in construction DT. This is achieved through the analysis of keywords using the network visualisation map in VOSviewer. This map, unlike the network visualisation map, includes a time bar showing the years in corresponding numbers to different clusters on the map. From figure 11, the area for future research referred to here as the colour red indicates hot topics. The budding technologies identified for future research and full integration into the construction industry processes are blockchain technology, cloud computing, green building technology, 3D printing, digital fabrication, wearable technologies, CPS, IoT, wireless sensor networks, and unmanned aerial systems.

Meanwhile, organisations are to focus on change management in response to the external force of DT; there is also a need for more focus on small to medium-sized organisations adoption and response to DT, inter-firm collaborations and mergers in response to DT, the impact and response of organisational culture and structures to DT requires more research in the construction industry.

Furthermore, the use of DT in facilities management cost estimating and quality assurance in construction. The impact of DT on project success, project teams and stakeholders and offsite construction. Research is also required on the use of DT on energy consumption and performance, energy-saving and use, environmental regulations and renewable energy sources for the construction industry. Figure 12 shows an overview of the research focus and the areas of future directions for construction DT.

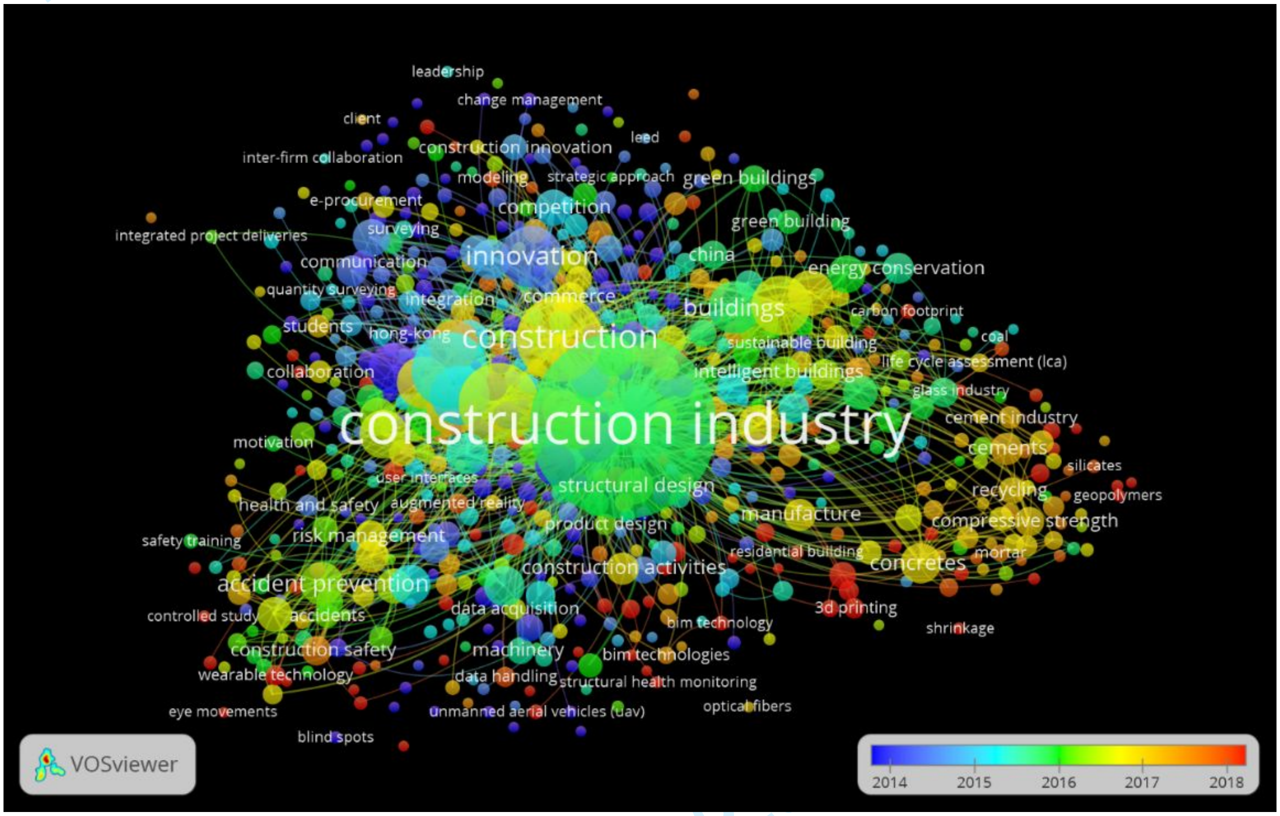

Figure 11: Overlay visualisation

8 Conclusion

The digitial transformation revolution is changing every sector greatly and making them become more productive and efficient. Unlike other industries, the construction industry has always been notorious for late transformation technologically. This tradition, has been found to be counter productive and there have been several studies and efforts to understand and counter this. This is due to the inherent benefits in these ~~transfromations~~transformations. In order to understand and establish the scorecard of the construction industry in the present digital transformation era, the study reviewed the DT journey in the AECO sector between 2010-2020 and identified the different aspects of DT in the AECO sector.

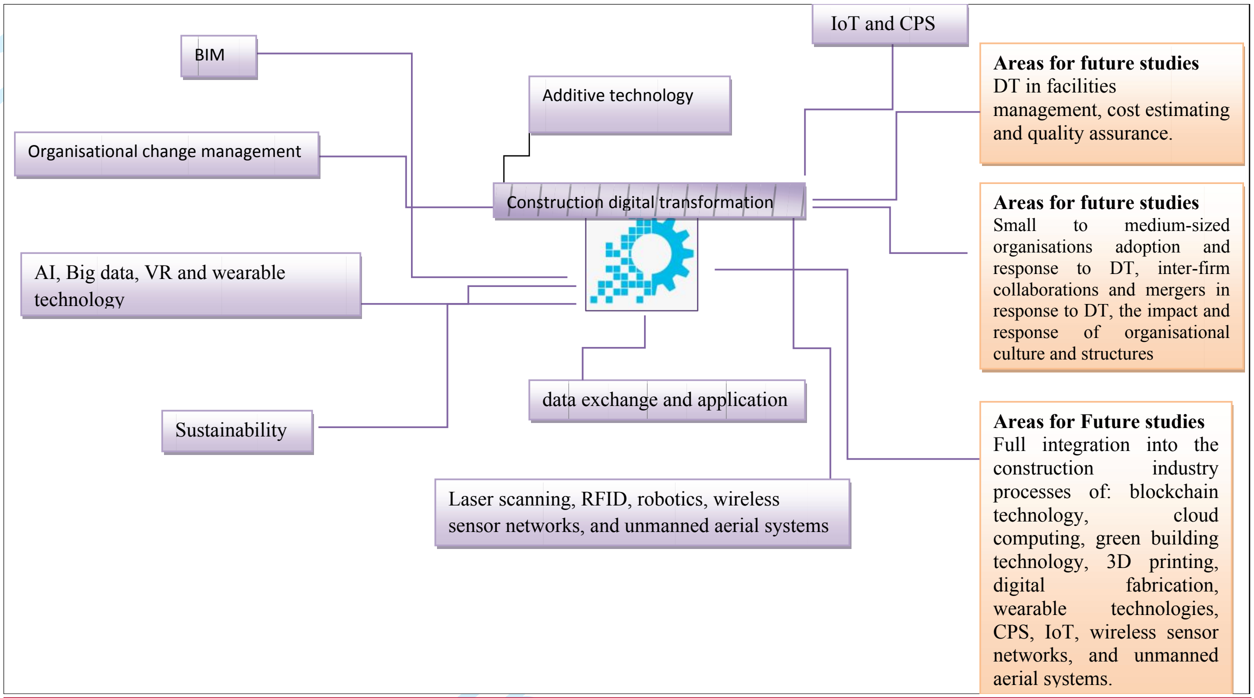

Figure 12:Research focus and areas for future study

The study results demonstrate, among other findings, the following:

1. This study was able to show that DT is beyond the technologies as it affects different aspects of the industry. It articulates the DT developments in the AECO sector and provides an outlook on the future research areas in the sector.
2. The study identified the different aspects of DT in the AECO sector. Furthermore, building on the existing flow model of DT discussion, the study developed a flow model for the discussion of DT in the construction industry.
3. For the past decade, the construction industry has focused more on BIM implementation. However, recent digital transformation efforts in the construction industry ~~has~~ have witnessed the integration of emergent technologies with BIM and the construction process.
4. The digital transformation discusses in the construction industry consists of different phases and aspects. This makes it different from other industries. This also gives credence to the peculiarity of the construction industry and it, by extension, means more efforts are needed to achieve digit~~i~~al transformation in the construction industry.

The study findings are important as they demonstrate that the construction industry unlike in the previous technological transformation eras~~,~~ have been very active in the area of digital transformation in the last decade. It provides a basis for ~~the~~ digital transformation ~~researhc~~ research in the construction industry. This study has both research and practical implication; however, it has some shortcomings as it gathered data from the SCOPUS database; thus, other databases were not considered.

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Appendix

Cluster 1

Technology			Organisation			Project		
keyword	Freq	total link strength	keyword	Freq	total link strength	keyword	Freq	total link strength
Blockchain	9	32	Change management	9	47	Building performance	8	35
Cloud computing	8	56	Competitive advantage	21	138	Construction stakeholders	9	52
Digital technologies	15	93	Competitiveness	13	59	Construction supply chain	15	124
Digitalization	6	11	Inter-firm collaboration	5	23	Environmental sustainability	9	75
Green building technologies	5	37	Knowledge sharing	10	40	Facilities management	5	32
ICT	14	65	Organizational culture	8	37	Procurement	11	67
Information and communication technologies	40	287	Organizational innovation	5	26	Project management	236	1571
			Organizational performance	5	25	Project success	5	15
			Organizational structures	8	48	Project team	13	89
			Small to medium-sized enterprises	5	19			

Cluster 2

Technology			Project			Sustainability		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
3-d printing	13	100	Construction and demolition waste	10	79	Eco-design	6	69
3d printers	29	194	Construction material	6	60	Emission control	24	239
3d printing	16	113	Construction waste	7	51	Energy	6	33
Additive manufacturing	16	95	Construction wastes	10	93	Energy conservation	38	302
Digital fabrication	8	41	Glass fibers	5	27	Energy consumption	5	50
Energy efficient technology	5	47	Retrofitting	6	51	Energy dissipation	5	34
Energy-saving technologies	6	51				Energy efficiency	82	590
Green manufacturing	8	67				Energy performance	5	31
Green technology	6	41				Energy policy	10	111
Nanotechnology	7	17				Environmental pollutions	5	43
Microstructure	5	33				Energy saving	6	36
Scanning electron microscopy	9	54				Energy use	7	67
						Environmental protection	13	116
						Environmental regulations	5	51
						Gas emissions	19	176
						Green building	23	142
						Green construction	6	39
						Greenhouse gases	26	271
						Renewable energy resources	8	91

Sustainable construction	30	185
Sustainable development	139	1112
Thermal insulation	10	67

Cluster 3

Technology			Data exchange			Applications		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
3d modeling	7	76	IFC	5	28	Quality control	22	168
BIM	106	535	Industry foundation classes - IFC	8	77	Scheduling	15	127
Building information model - BIM	95	780	Information analysis	8	79	Facility management	6	49
Building information modeling	59	390	Information exchanges	10	85	Architectural design	255	1906
Building information modeling (BIM	30	200	Information modeling	5	32	Cost benefit analysis	33	290
Building technologies	9	63	Information sharing	6	55	Cost estimating	10	99
Computer aided design	26	208	Data acquisition	19	142	Design and construction	20	142
Information technologies	20	172	Data visualization	11	120	Simulation	20	135
			Interoperability	11	101	Three dimensional computer graphics	18	157

Cluster 4

Applications			Technology		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
Accident prevention	73	591	Artificial intelligence	12	83
Ergonomics	10	84	Big data	9	45
Hazard identification	8	62	Deep learning	5	24
Health and safety	20	118	Knowledge based systems	17	138
Image processing	5	32	Neural networks	11	76
Occupational accident	9	80	Virtual reality	27	202
Occupational health and safety	5	44	Wearable technology	17	121
Occupational risks	49	410			
Occupational safety	14	138			
Protective clothing	6	53			
Safety engineering	25	218			
Safety management	19	147			
Safety performance	12	79			

Cluster 5

Technology			Benefits			Construction project		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
Cyber physical system	7	65	Quality assurance	5	41	Construction productivity	12	80
Cyber-physical systems	5	30	Real time monitoring	7	41	Construction quality	6	50
Cyber-physical systems (cps)	5	48	Standardization	11	69	Lean construction	19	132
Internet of things	18	113				Lean production	12	83
Internet of things (IOT)	10	70				Modular construction	18	105
						Off-site construction	7	46
						Off-site manufacturing	5	24
						Offsite construction	5	33
						Prefabricated construction	14	112
						Prefabrication	18	92
						Productivity improvements	12	86

Cluster 6

Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq
Laser applications	13	101	Construction planning	10	66	Underground construction	7
Laser scanning	9	68	Life-cycle management	5	38		
Radio frequency identification	5	51	Resource allocation	6	39		
Radio frequency identification (RFID)	31	256					
Radio frequency identification technology	6	55					
Real-time information	8	85					
Remote sensing	6	44					
RFID	12	101					
RFID technology	5	41					
Robotics	20	104					
Sensors	7	41					
Unmanned aerial systems	5	31					
Wireless sensor networks	5	46					

The research search string

TITLE-ABS-KEY("construction industry" AND "technology" OR "Innovation" OR "industrial revolution" OR "Digitisation") AND (EXCLUDE (PUBYEAR,2021)) AND (LIMIT-TO (SUBJAREA,"ENGI")) AND (LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011) OR LIMIT-TO (PUBYEAR,2010)) AND (LIMIT-TO (DOCTYPE,"ar"))

DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY: A BIBLIOMETRIC REVIEW

RESPONSE TO REVIEWERS COMMENTS

The authors wish to thank the reviewers for their time and comments to enhance this manuscript. Please find below the response to the reviewers' comments.

Thank you.

Reviewer: 1

The authors are grateful for all of the objective comments.

- In Section 2, there are some citations about Digital transformation (DT), but is there any standard definition for that? How did you make sure to include and exclude correct items in your study?

RESPONSE: There is no standard definition of DT; to this end, the study examined various definitions existing in literature. Consequently, a definition by the study has also been included.

- How to make sure terns in L19P6 are exclusive?

RESPONSE: The adopted terms for the study is based on literature review. This is presented in Table 1.

- Does Fig 3 follow any similar trends in other area?

RESPONSE: Yes, there is a similar trend in BIM adoption in developing countries(Adekunle, Ejohwomu, and Aigbavboa 2021).

- How countries were determined, in case there was no location data?

RESPONSE: This comment is unclear but if it refers to the countries in the analysis. They were derived from data collected and extracted through the analysis.

- Citations have recently been used to determine author influence in bibliometric

RESPONSE: The study adopted publications, and this has also been adopted recently (Aghimien et al. 2021).

- Studies. So can you conclude that older papers are more influential?!

RESPONSE: Based on the results, yes, they are; this might be unconnected to the fact that these publications provided the foundation for other/newer publications.

- What is the use of author output?

RESPONSE: This has been justified in the manuscript. It shows authors productivity in the study and major players over time.

- Shapes should be redone

RESPONSE: What shapes does this refer to, please?

- Where are the terms in Table 3 coming from?

RESPONSE: *Table 4* contains terms from data analysis.

- What is the use of figure 9?

RESPONSE: As stated in the manuscript, it shows the hot topics based on generated maps using network analysis.

- How do you explain three aspects of DT which are technology, organisational behaviour and construction project aspects in Cluster 1?

RESPONSE: These were discussed based on the cluster keywords and related publications.

- How were the theme or aspects of each cluster determined?

RESPONSE: The theme of each cluster is informed by the keywords making up the clusters.

- What is the process Figure 10: Flow model for construction DT?

RESPONSE: the process follows that in (Verhoef et al. 2021). However, this is modified to the construction industry.

Reviewer: 2

The authors are grateful for all of the objective comments.

- What is included and excluded as part of digital transformation in construction? Provide the final definition of digital transformation adopted in the study.

RESPONSE: This is now provided for in the manuscript and highlighted.

- The gap that the paper is trying to fill is unclear. Also, there are many review papers on similar topics. Therefore, suggest adding a paragraph or subsection on what other similar review papers exist on the topic. Then, provide the gap that the paper is trying to fill.

RESPONSE: Similar papers are on different technologies and not the DT in the construction industry.

- Which part of the results relates to the paper's third objective? It seems a bit hard to find it. Maybe adding specific subsections to present the results would be helpful.

RESPONSES: This has been Corrected

- How many from the 1892 papers are related to DT?

RESPONSE: ALL, the authors went through the collected data to ensure this.

- Page 7, line 21. Is the statement true?

RESPONSE: this is unclear. Which statement do you refer to, please?

- Are there any process to ensure that the papers identified through the search string were related to DT?

RESPONSE: YES, the data file downloaded from Scopus was checked.

- How were the normalised TC values calculated? Also, what do the results mean for this study?

RESPONSE: The data was analysed using Biblioshiny to achieve the values; the implication has been included in the manuscript.

- Add discussion for Figure 6

RESPONSE: Done

- 5.5 Authors outputs. It seems like the end of the paragraph was accidentally cut.

RESPONSE: corrected

- Page 14, Line 21, do you mean Figure 6?

RESPONSE: Corrected

- Table 3. What is the difference between new technologies, technology, and innovation? For example, what is the difference between building information modelling and building information modeling? Why were they separated and not combined?

RESPONSE: Table 4: it is a trend, referring to different years and the trending keyword.
- Add each cluster's name in their respective subsection to better illustrate each subsection.

RESPONSE: Done

- How was Figure 10 developed?

RESPONSE: It was generated using network analysis through Vos viewer.

- Suggest adding more future directions based on the gaps identified from each cluster.

RESPONSE: Please see the revised manuscript.

Reviewer: 3

The authors are grateful for all of the reviewer's objective comments.

Thank you

DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY: A BIBLIOMETRIC REVIEW

RESPONSE TO REVIEWERS' COMMENTS

The authors are grateful to the reviewers for their constructive feedback and comments for a better manuscript. Please find below the responses, these are highlighted in yellow.

Reviewer 1

"In Section 2, there are some citations about Digital transformation (DT), but is there any standard definition for that? How did you make sure to include and exclude correct items in your study?", the authors have responded "There is no standard definition of DT; to this end, the study examined various definitions existing in literature. Consequently, a definition by the study has also been included." which indicates the second part of the comment is left behind.

The authors wish to thank the reviewer for this comment. The steps taken to achieve correct items inclusion for the study is explained briefly here: after searching for related publications using the search string, the criteria for inclusion and exclusion was applied. Afterwards, the result was scrutinized to ensure that it aligns appropriately. This is explained in the methodology section.

The second comment reads "How to make sure terns in L19P6 are exclusive?" and the authors responded," The adopted terms for the study is based on literature review. This is presented in Table 1." while Table 1 does not show aforementioned terms.

We appreciate your comment.

Your comments were interpreted to mean the keywords adopted in the study for the search string. Table 1 contains keywords derived from previous studies on DT and they formed the basis for the study.

Subsequently, the next comment was "Does Fig 3 follow any similar trends in other areas?" which was responded by "Yes, there is a similar trend in BIM adoption in developing countries(Adekunle, Ejohwomu, and Aigbavboa 2021)." This response does not show where (and how) in the paper this trend is seen for other areas.

Apologies for not showing this in the previous response. It is shown on Page 7, section 5.1: the similarity is observed in the output trend.

Reviewer 2

What is included and excluded as part of digital transformation in construction? Provide the final definition of digital transformation adopted in the study. Which part was highlighted to address this comment? I've tried to go through the edits but still could not find the answer.

The authors appreciate the reviewers comment, the definition can be found on the First paragraph on page 3, highlighted in yellow

- The gap that the paper is trying to fill is unclear. Also, there are many review papers on similar topics. Therefore, suggest adding a paragraph or subsection on what other similar review papers exist on the topic. Then, provide the gap that the paper is trying to fill. (What is your proof that there are no similar papers on different technologies and not the DT in the construction industry?)

The authors are appreciative of this observation and comment.

There are various works focusing on different 4IR technologies (as cited in the manuscript) and there are some on construction DT for instance Papadonikolaki, Krystallis, and Morgan (2020). However, the scope of this study and the adopted methodology are different from that of similar works in this area. Page 2

- How do you validate that all 1892 papers are DT papers? Suggest explaining in the manuscript itself so others can replicate the methodology.
- What is the process to ensure that the papers identified through the search string were related to DT? Suggest explaining in the manuscript itself so others can replicate the methodology.

Thank you for this suggestion. Your comment has been included on Page 7, first paragraph.

- If Table 3 shows a trend, why do we need to separate 'building information modeling' and 'building information modelling'? Are they both not the same and should be combined to show a better trend?

The authors appreciate this comment. The table has been reviewed accordingly. Page 15

DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY: A BIBLIOMETRIC REVIEW

Abstract

Purpose- The construction industry has been traditionally referred to as slow when it comes to technological transformation. To investigate and present a scorecard of the construction industry in the last decade, the paper adopted Bibliometrics. The study identified the various digital transformation aspects in the construction industry and future research directions~~ are also identified~~.

Design/Methodology/Approach- To achieve the aim of this research, an inductive approach was adopted through a grounded theory strategy. Secondary data was retrieved from the Scopus database and analysed using Biblioshiny and VOSviewer. The data was retrieved through specific keywords related to the study focus.

Findings- The data analysis reveals that the construction industry has been active regarding the digital transformation drive in the last ten years. However, ~~there are countries that~~some countries are still lagging~~ in this regard, ~~; the study identified and classified digital transformation in different countries accordingly. Digital transformation in the construction industry disrupts every aspect of the industry, albeit at different rates due to the existing barriers; hence the study identified areas that require further research. The study also proposed a balanced flow model for digital transformation discussion in the construction industry.

Limitations- The study adopted a single database for data collection.

Value- It is worthy of note that this is the first study that analyses the digital transformation in the construction industry in the last decade using the adopted methodology. The study maps the construction industry research efforts on digital transformation and provides an assessment of the construction industry in terms of digital transformation. It thus provides a theoretical and practical basis for researchers and practitioners alike.

Keywords: bibliometric, construction industry, digital transformation, industry 4.0, literature review, scientometrics, technological revolution

1 Introduction

The construction industry has been assessed to be a slow responder to technological advancement. Literature is replete with studies comparing the construction industry to other industries and concluding that the industry, unlike others, does not adopt and implement technologies swiftly(Castagnino, Rothballer, and Gerbert 2016). This aligns with (Fitzgerald et al. 2013) that lack of urgency is a major barrier to achieving digital transformation. This has led to a meagre productivity rate of the construction industry (WEF and BCG 2016), but this narrative seems to have changed recently. This can be attributed to the rapid industrial revolution in other sectors and the COVID-19 pandemic. These two cited reasons have a disruptive effect on the construction industry. Their impact has become a major driving force towards technological tools adoption in the construction industry.

Recently, there have been different studies on the adoption of various technologies in the construction industry. These technologies include but are not limited to RFID (Osunsanmi, Oke, and Aigbavboa 2018), robotics (Aghimien et al. 2019; Davila Delgado et al. 2019), Blockchain technology (Turk and Klinc 2017), BIM (Kassem et al. 2014; McGraw Hill 2014), IoT (Tang et al. 2019) and sensors (Kán et al. 2021). Mostly, the discussion has been on exploring the potentials of these individual technologies and their impact on the construction industry's productivity. A study by Papadonikolaki, Krystallis, and Morgan (2020) using thematic analysis discussed the DT in construction industry from 1950 to 10 June 2018. The study focused on the use of DT, implications on professional, projects and organisations and the future direction. Consequently, there exists a dearth in the holistic study of DT in the construction industry recently in the last decade. In the light of recent technological developments, this study aims to map the digital transformation efforts and aspects in the construction industry.

The importance of this study cannot be overemphasized, this study presents a one-stop, state of the art presentation of the digital transformation journey in the construction industry. This status will provide a critical analysis and provide a way forward in the digital transformation drive of the construction industry. Also, it provides a pathway for stakeholders in achieving comprehensive digital transformation of the industry. Therefore, librating the construction industry from the age-long stigma of lack of urgency in technological adoption.

2 Digital transformation (DT)

DT is highly disruptive; it disrupts markets considered to be highly regulated (Leong et al. 2017). To properly situate and understand the concept of DT; this study searched for the definition of digital transformation. This is important to establish the meaning and aspects of the concept. Extant literature was consulted to achieve this. All changes brought about by digital technology in all aspects of human life has been referred to as DT(Stolterman and Fors 2004). This definition puts forward the unrestricted disruption brought by DT. It can be said that DT thus changes everything about human living and the conduct of everyday business. This is unsurprising as the human plays different roles in the social network in relation to DT. ~~(~~Westerman et al. (2011) define~~s~~ DT as the employment of technology in order to radically improve the performance of enterprises. This definition emphasises the radicality and improvement that comes with DT, especially for business enterprises~~.~~ .

Consequently, no sector or organisation has been shown to be immune to the effects of DT (Hess et al. 2016). ~~Furjan et al. (~~Furjan, ~~Tomičić-Pupek, and Pihir~~et al. (2020) describe it as a "digital technology-based improvement" to the business process. ~~(~~Matt~~, Hess, and Benlian~~et al. (2015) describe~~s~~ DT *as "a continuous complex undertaking that can substantially shape a company and its operations*". ~~Mahraz et al. (~~Mahraz, ~~Benabbou, and Berrado~~et al. (2019) describe DT as a disruptive change process. Using the works of (Akmajian et al. 2001; R. Suddaby 2010; Wacker 2004), (Vial (2019) was able to construct a conceptual definition for DT. According to (Vial 2019), DT is *"a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies"*. This definition refers to DT as a process that achieves measurable changes through ICCCT. Based on these definitions, the study defines: Construction DT involves the significant, disruptive change to construction processes (vertically, horizontally and longitudinally) for improving construction output and productivity to achieve project outcome and better client satisfaction through the adoption of information, computing, communication, and connectivity technologies.

To achieve DT, different drivers have been identified in literature. Nadkarni and Prügl (Nadkarni and Prügl (2020) classified these drivers into two: technology and actor. Meanwhile, (Hrustek, et al.Tomicic Furjan, and Pihir (2019) classified it into customer, technology and organisational development drivers. (Verhoef et al.(2021) adopted three drivers for their study, which are: Digital Technology, Digital Competition and Digital Customer Behavior. From the identified drivers, it is evident that technology is not the only ingredient to achieving DT. Hence it is wrong for sectors to focus on the technologies required without consideration for other drivers required for DT.

Table 1: Challenges, benefits and some identified DT technologies.

Table 1: Challenges, benefits and some identified DT technologies.

	Reference	Challenges
Challenges	(Fitzgerald et al. 2013)(Westerman et al. 2011)(Yucel 2018)	Lack of impetus, Regulation and reputation, Unclear business case, Missing skills, Culture issues, IT Difficulties, Governance challenges, lack of urgency, Not enough funding, Limitations of IT systems, Roles and responsibilities are not clear, Lack of vision, Unclear business case, Business units implementing independently in silos, Culture not amenable to change, Lack of leadership skill, Regulatory concerns, strategy related, support and sponsorship-related, implementation-related
Benefits	(Fitzgerald et al. 2013)(Hess et al. 2016)(Capuşneănu et al. 2021)(Westerman,	productivity improvements, cost reductions and innovation, better customer experiences and engagement, streamlined operations and new lines of business or business models, organisational efficiency, organisational agility, manufacturing innovation, product quality and

	Bonnet, and Mcafee 2014)(Schwertner 2017)	safety and process improvement, streamline workflow and improve productivity
Keywords employed in DT research	(Mahraz et al. 2019; Nadkarni and Prügl 2020; Reis et al. 2018)	Industry 4.0, Digital business enterprise architecture, digital transformation, digitisation, IoT, internet, Innovation, technology, digitalisation
Identified technologies		Big Data Analytics, IoT, cloud computing, blockchain, big data, mobile technology, 3D printing

Achieving DT is requires change by firm, processes and the ecosystem. Old firms are required to embrace new organisational structures and processes in order to blend with the DT trend(Sebastian et al. 2017). Furthermore, they must adopt the technologies suited for the transformation in their line of work. Although it has been established that adopting all technologies is not the prerequisite for DT. DT can be attained without necessarily adopting all the technologies (Yucel 2018). ~~Verhoef *et al*~~. ~~(~~Verhoef et al. (2021) presented a flow model for discussion of DT, which hints at the different aspects of DT (Figure 1). Transiting from the status quo and achieving DT, organisations will have to overcome hurdles. Table 1 presents a list of hurdles, benefits and technologies for achieving DT.

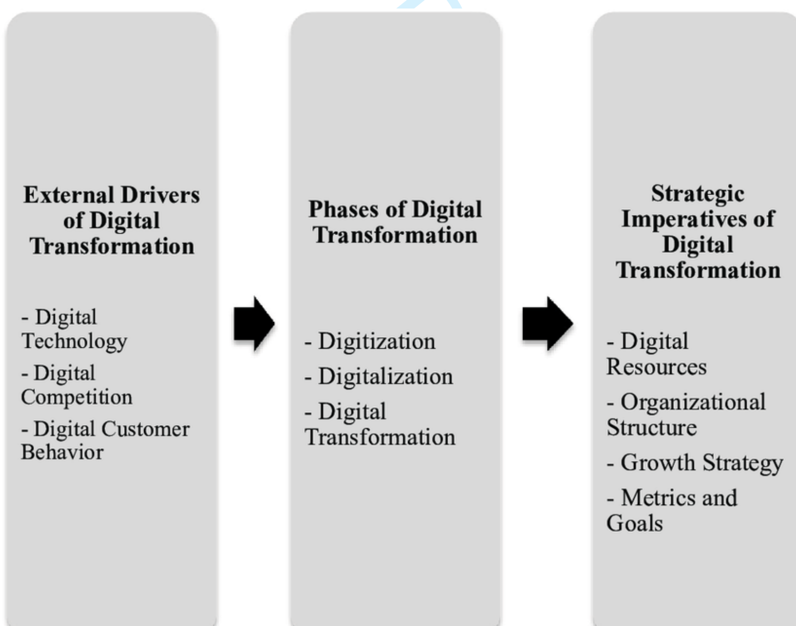

Figure 1: Flow model on DT discussion (Verhoef et al. 2021)

3 Summary and gap

A critical analysis of the works on DT reveals that, although it involves changes made possible by technology but it is not just about the technologies. It also affects every aspect of human endeavours. It can also be inferred that it is a disruptive yet continuous process. It is, therefore, the aim of this paper to map the completeness of the DT drives in the construction industry. With this study, the following objectives are to be achieved: (1) Conduct a literature analysis using themes of the digital transformation of the construction industry, (2) To articulate the technologies adopted in the construction industry towards achieving DT and (3) To identify the research frontiers, hot topics and future trends. based on the other drivers identified, this study will critically analyse the DT drivers peculiar to the construction industry. This study is important to the industry and its drive to achieve DT. It also provides practitioners with an insight into the state of the industry and what is required.

4 Research methodology

This study aims to articulate the progress made in achieving DT of the construction industry research. Bibliometrics was chosen to achieve this because this method is used to primarily answer three questions, which are outlined below(Aria and Cuccurullo 2017): (i) identify the knowledge base of a research field and the intellectual structure; (ii) examine the research front (or conceptual structure) of the research field; (iii) produce a social network structure of a particular scientific community

Through this methodology (illustrated in figure 2), the study achieved the following: (i) the most cited documents; (ii) the most productive and consistent authors; (iii) the trend words; (iii) DT drivers and aspects in the construction industry. The research methodology for this study is discussed under five headings based on the standard workflow for bibliometric mapping (Zupic and Cater 2015). These five headings are study design, data collection, data analysis, data visualisation and interpretation.

4.1 *Study design*

Study design entails the definition of the study research questions and making the choice of appropriate methods to achieve it(Aria and Cuccurullo 2017). Other decisions made at this stage include the timespan, keywords, selection of the database, the software for data analysis, among others, to achieve the study objective.

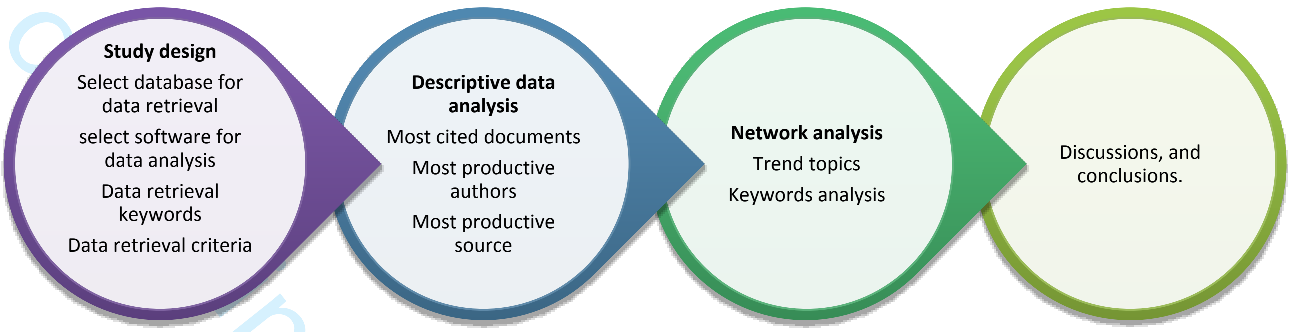

Figure 2: Study research design

4.2 *Data collection*

To achieve data collection for this study, the Scopus database was adopted. Literature has established that there are other databases like PubMed, Web of Science and Google Scholar, and these databases have peculiarities (Falagas et al. 2008; Harzing and Alakangas 2015; Martín-Martín et al. 2018). The Scopus database was chosen for this study because it is considered more comprehensive(Mongeon and Paul-Hus 2016) and has been adopted by various studies for bibliometric review (Jin et al. 2019; Newman et al. 2020). Furthermore, the Scopus database presents the widest pool of digital peer-reviewed publications(Newman et al. 2020). It thus provides an extensive and up to date relevant database for the present study on digital transformation. The search for publications was based on keywords. These keywords are either found in the title, abstract or keywords of publications. The documents retrieved are based on those having the selected keywords. For this study, the keywords adopted is ("construction industry" AND "technology" OR "Innovation" OR "industrial revolution" OR "Digitisation"). Appendix 1 provides the search string for the study.

To properly focus the data retrieved for the study, the study adopted a time frame of 2010-2020. This is in order to map the recent advancements effectively in the construction industry towards achieving DT. In line with achieving currency of data, the study adopted only journal articles. Thus, other types of publications were excluded (i.e. conference proceedings, books, book chapters, among others). Journal articles are considered to publish current research findings and efforts and are also believed to be more rigorous and detailed when compared to conference proceedings. Extant literature has also adopted using only journals for similar studies (Jin et al.

2018; Ramos-Rodrígue and Ruíz-Navarro 2004; Zheng et al. 2016). Another reason for settling for journal articles was because most conferences were affected by the Coronavirus pandemic; hence many were postponed and some cancelled. Search output was further pruned by applying the subject area criteria by restricting publications only to the engineering field. A total of 1892 articles were returned and considered by this study from the initial 11,428 documents returned before the screening. All 1892 publications were screened using their abstract and title to ensure the collected data are aligned to the study. Downloaded scopus file was opened as a spreadsheet and the publications scrutinized for alignment with construction DT using Ms excel.

4.3 *Data analysis*

Although there are numerous software to analyse bibliometric data as chronicled by (Cobo et al. 2011; Moral-Muñoz et al. 2020), however, in order to fully retrieve all information from the rich data collected, this study analysed its data using Biblioshiny and VOSviewer. These two software have been adopted for data analysis in literature; however, a combination of the two is not commonplace. Biblioshiny was adopted majorly for the descriptive analysis, while the visualisation was achieved using VOSviewer.

Biblioshiny is a version of Bibliometrix for non-coders. It is powered by Bibliometrix (Aria and Cuccurullo 2017); however, Biblioshiny is web-based. It works with Scopus, Web of Science, Dimensions, Pubmed and Cochrane library. Biblioshiny was chosen for the descriptive data analysis. It possesses a well organised and intuitive interface (Moral-Muñoz et al. 2020).

VOSviewer (van Eck and Waltman 2019; Jan van Eck and Waltman 2006) is primarily a visualisation software. It is employed for creating maps based on the data. Networks primarily contain items and links. Items are the objects being studied, while links show the relations between two items (van Eck and Waltman 2019). Links connect two items. VOSviewer has been used for bibliometric study in similar studies in the digital transformation era; for instance, (Aghimien et al. 2019, 2020, 2021; Chellappa, Srivastava, and Salve 2021; Safura Zabidin et al. 2020) employed it in mapping industry 4.0 in the construction industry and digitalisation studies, workers health and safety, computational modelling respectively. ~~Visulaisation~~ Visualisation has been popularly adopted in ~~vatious~~ various construction industry research domains (Babalola et al. 2021; Mariam, Olalusi, and Haupt 2020).

5 Interpretations and discussions

5.1 *Progression of publications*

Considering the laid back nature of the construction industry in terms of digital transformation, it is essential to investigate the research outputs in this space. This output is an indication of researchers efforts in achieving DT in the construction industry. Figure 2 shows the details of the research outputs from 2010-2020. From the figure, there is an upward increase in the DT research output in the construction industry. The observed trend is similar to the observed trend in BIM uptake in the construction industry observed by Adekunle, Ejohwomu, and Aigbavboa

(2021). In thebeginning, the output was unstable but positive upward trend in latter years. Aside from 2011 and 2014, where the outputs dipped, consequent years have experienced a steady upward trend. This is an indicator that the construction industry is steadily making conscious efforts to achieve DT.

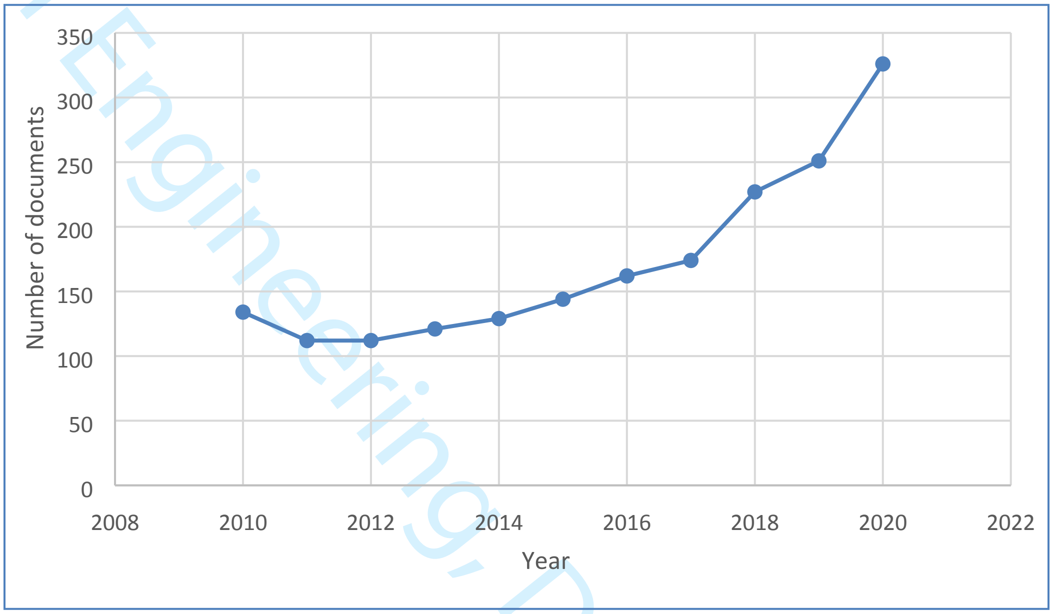

Figure 3: Construction DT publication output between 2010-2020

5.2 *Geographical DT research efforts*

To identify the knowledge contribution on a geographical basis, the global contribution of various countries was analysed. Figure 1 presents the frequency of these countries. China leads with 497 documents, followed by the USA with 481 documents.

Table 1 presents a classification of countries adopted by this study based on the number of documents contributed by these countries. Countries with more than 100 documents were classified as DT leaders, and DT contemplators were those countries with documents lesser than 100 but greater than 50. Furthermore, DT strugglers and DT Laggards were terms used to describe countries with less than 50 documents but more than ten and less than ten, respectively.

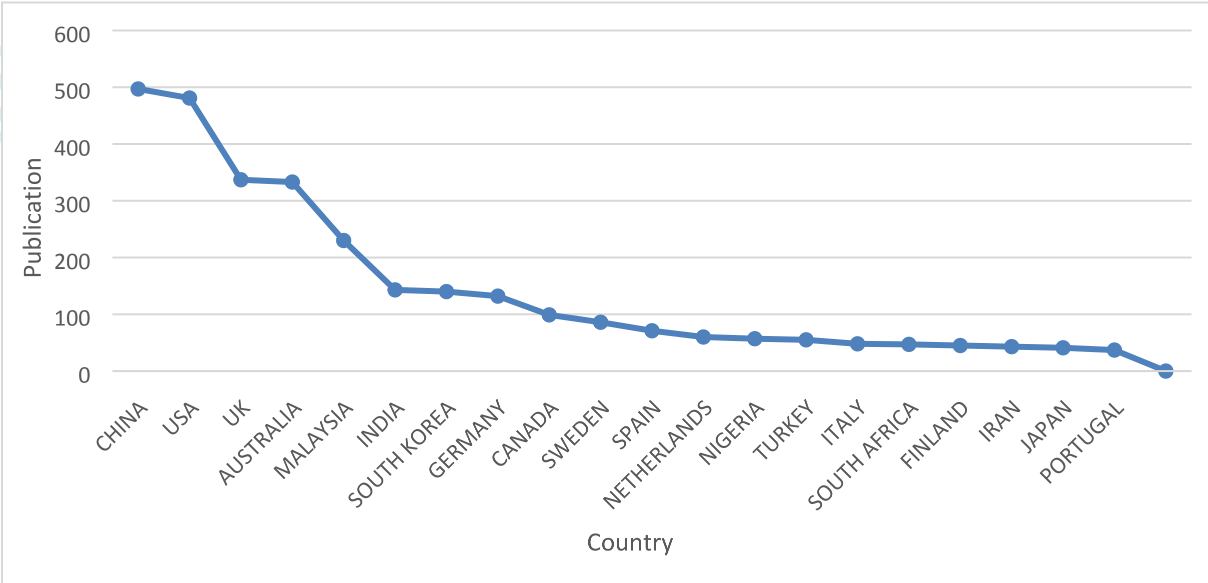

Figure 4: Geographical publication statistics

A critical analysis of Table 21 reveals that most countries that were referred to as BIM leaders are also DT leaders. According to (Edirisinghe and London (2015), the USA, UK, South Korea, and Australia were referred to as BIM leaders. Other BIM leaders, according to (Edirisinghe and London 2015), are Hong Kong, Singapore, Norway and Finland.

Table 2: Classification of countries based on publication

Classification	Countries	Nr of documents
DT leaders	China, USA, UK, Australia, Malaysia, India, South Korea, Germany	Greater than 100
DT contemplators	Canada, Sweden, Spain, Netherlands, Nigeria, Turkey	Greater than 50
DT strugglers	Italy, South Africa, Finland, Iran, Japan, Portugal, France, Pakistan, Israel, Czech Republic, Jordan, Slovakia, Slovenia	Less than 50
DT laggards	Ireland, Indonesia, Iraq, Sri Lanka, Qatar, Cyprus, Argentina, Bangladesh, Colombia, Ethiopia, Greece, Kazakhstan, Kenya, Lebanon, Mexico, Morroco, Oman, Serbia, Ukraine, Yemen, Hungary, Kuwait, Uzbekistan, Croatia, Latvia, Philippines, Romania, Bulgaria, Cameroon, Iceland, Kyrgyzstan, Liberia, Luxembourg, Macedonia, Mozambique, Peru, Rwanda.	Less than 10

Although the latter four are not DT leaders, however, others are. This brings about the question of if the digital divide is never going to be closed up. Also, it gives credence to the Matthew effect summarised simply as the rich getting richer and the poor getting poorer. Although (Van Dijk and Hacker 2003) posits that early adopters bear the most burden of implementation as they pay for innovation, thereby making it cheaper for late adopters. The question with this position as it affects the construction industry is if the innovation is subsidized enough for late adopters. If late adopters can adopt it, most times while late adopters are still struggling to adopt the last, there is a new innovation or an upgrade. This mostly puts the late adopters in a difficult position of catching up and closing the digital divide.

5.3 *Influential publications*

This section discusses the most cited documents or publications in the construction DT space in the last decade. Citations have recently been used to determine author influence in bibliometric studies (Saka and Chan 2019; Wang et al. 2020). Table 32 presents the top 20 most cited construction DT publications. (Zabalza Bribián, Valero Capilla, and Aranda Usón (2011)'s work remains the most cited. The normalized total citation column makes it possible for the benchmarking and comparison of documents. A critical look at the table suggests that BIM, 3D printing, VR/AR are some of the technologies focused on by the studies. However, BIM appears to be the most talked-about technology in the last decade in the construction industry. It can be inferred that BIM has enjoyed concerted attention from the industry. Furthermore, this might be inferred to mean that many construction industry stakeholders have a strong belief in BIM to change the status quo in the construction industry (Eastman et al. 2008).

5.4 *Influential Journals*

To establish the relevant and influential journal sources in the construction DT space, this study adopted the Bradford Law of 1934 and observed publication source growth (using Loess smoothing) in the subject area. Figure 4 and Figure 5 respectively present the graphical representation of these two approaches. Figure 6 presents the source growth trend of the publication sources.

Bradford's Law was formulated by a British mathematician, documentationalist and Librarian, Samuel C. Bradford (Jeremy Norman 1934). This law posits that in any given research space, there exist different classifications of sources. Bradford went further to categorise the sources into productive core sources, moderate producers and those constantly diminishing. Hence the first classification or zones are the most cited in the research field; the second zone enjoy average citations while the

Table 3: Most cited construction DT documents

~~Paper~~Reference	Source	~~DOI~~Publication title	Total Citations	TC per Year	Normalized TC
~~(~~Zabalza Bibián et al. (2011)	Building and Environment	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential	621	56.45	19.1551
~~(~~Gu and London (2010)	Automation in Construction	Understanding and facilitating BIM adoption in the AEC industry	444	37	12.4105
~~(~~Singh, Gu, and Wang (2011)	Automation in Construction	A theoretical framework of a BIM-based multi-disciplinary collaboration platform	333	30.27	10.2716
~~(~~Bos et al. (2016)	Virtual and Physical Prototyping	Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing	316	52.67	17.2771
~~(~~Sacks, Koskela, and Dave (2010)	Journal of Construction Engineering and Management	The Interaction of Lean and Building Information Modeling in Construction	301	25.08	8.4134
~~(~~Arayici et al. (2011)	Automation in Construction	Technology adoption in the BIM implementation for lean architectural practice	277	25.18	8.5442
~~(~~Häkkinen and Belloni (2011)	Building research and information	Barriers and drivers for sustainable building	270	24.55	8.3283
~~(~~Teizer et al. (2010)	Automation in Construction	Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system	269	22.42	7.519
~~(~~Pomianowski, Heiselberg, and Zhang (2013)	Energy and Buildings	Review of thermal energy storage technologies based on PCM application in buildings	267	29.67	10.5821
~~(~~Qi et al. (2010)	Journal of Cleaner Production	The drivers for contractors' green innovation: an industry perspective	231	19.25	6.4568
~~(~~Miettinen and Paavola (2014)	Automation in Construction	Beyond the BIM utopia: Approaches to the development and implementation of building information modeling	208	26	10.7157
~~(~~Leung et al. (2015)	Materials and Structures	Review: optical fiber sensors for civil engineering applications	199	28.43	9.7969
~~(X.~~ Li et al. (2018)	Automation in Construction	A critical review of virtual and augmented reality (VR/AR) applications in construction safety	185	46.25	13.5163
~~(~~Cheng and	Automation in Construction	Real-time resource location data collection and visualization technology for	185	20.56	7.3321

Teizer (2013)		construction safety and activity monitoring applications			
(Dossick and Neff (2009)	Journal of Construction Engineering & Management	Organizational divisions in BIM-enabled commercial construction	177	14.75	4.9474
(Becerik-Gerber and Rice (2010)	Journal of Information Technology in Construction	The perceived value of building information modeling in the U.S. building industry	171	14.25	4.7797
(Pauwels and Terkaj (2016)	Automation in Construction	EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology	157	26.17	8.5839
(Eastman et al. (2010)	Journal of Computing in Civil Engineering	Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards	152	12.67	4.2486
(Pauwels et al. (2011)	Automation in Construction	A semantic rule checking environment for building performance checking	142	12.91	4.3801
(Li et al. (2015)	Safety Science	Proactive behavior-based safety management for construction safety improvement	141	20.14	6.9415

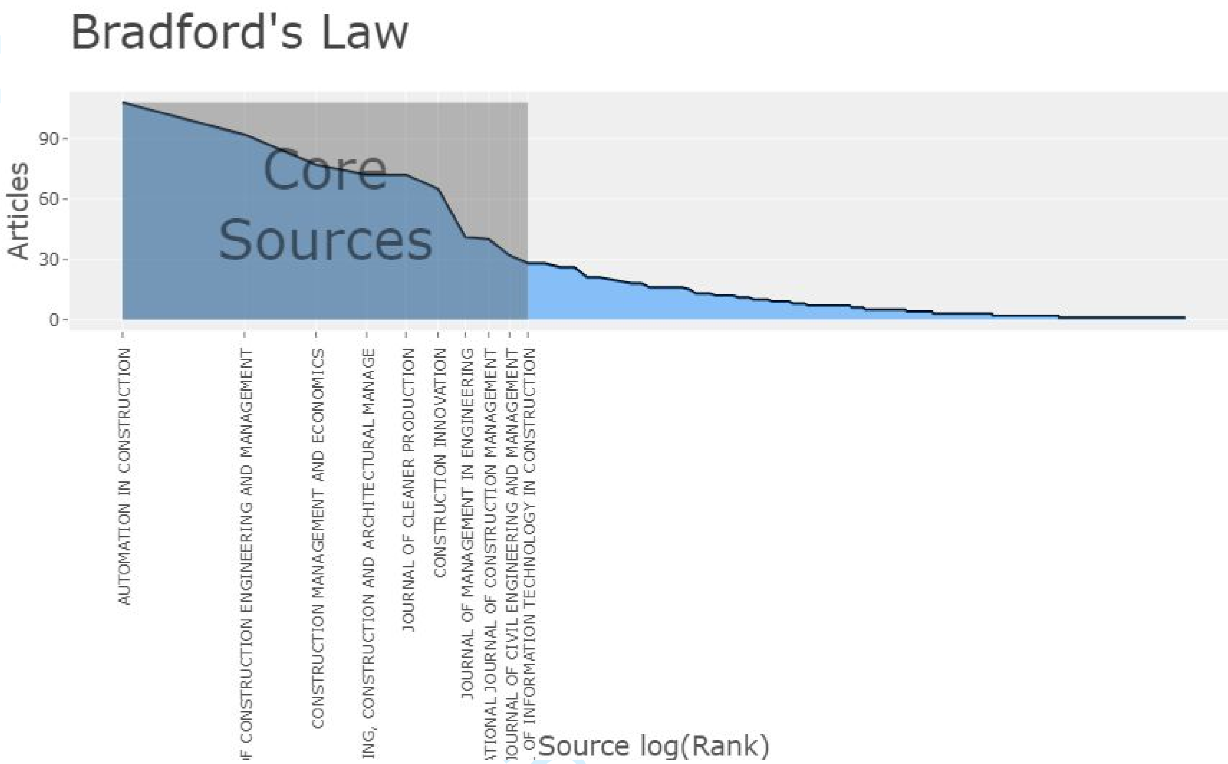

Figure 5: Core sources in construction DT

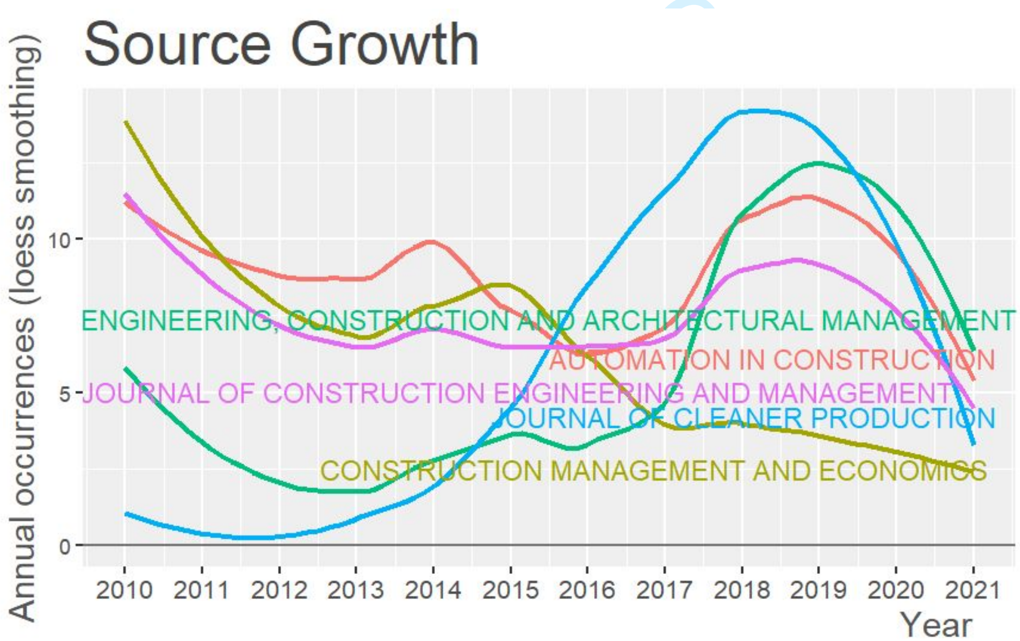

Figure 6: Annual source growth trend

third are seldomly cited respectively. In this order, this is employed to make reference to the importance attached to these sources. This law has been used for library stocking decisions and literature search decisions the world over [73]–[76]. The core sources of DT research is led by Automation in construction. The second core source is Construction Engineering and Management.

A study of the growth of these sources in DT research reveals that the Journal of cleaner production has experienced a strong upward growth more than other sources. This is followed by Engineering, Construction and Architectural management. However, this cannot be said of Construction management and economics, as it has experienced a steady annual decline.

5.5 Author outputs

Aside from the influences commanded by authors through the citations, it is also essential to articulate the top authors in terms of publications. This was similarly adopted by ~~(~~Aghimien et al. ~~(~~2021). Figure 7~~6~~ presents a trend of top-producing authors over the years. The top five producing authors are LI, H. with 21 publications, SKITMORE, M. with 19 documents, LIU, C. and TEIZER, J. having 13 publications each, and CHAN, A.P.C. contributing

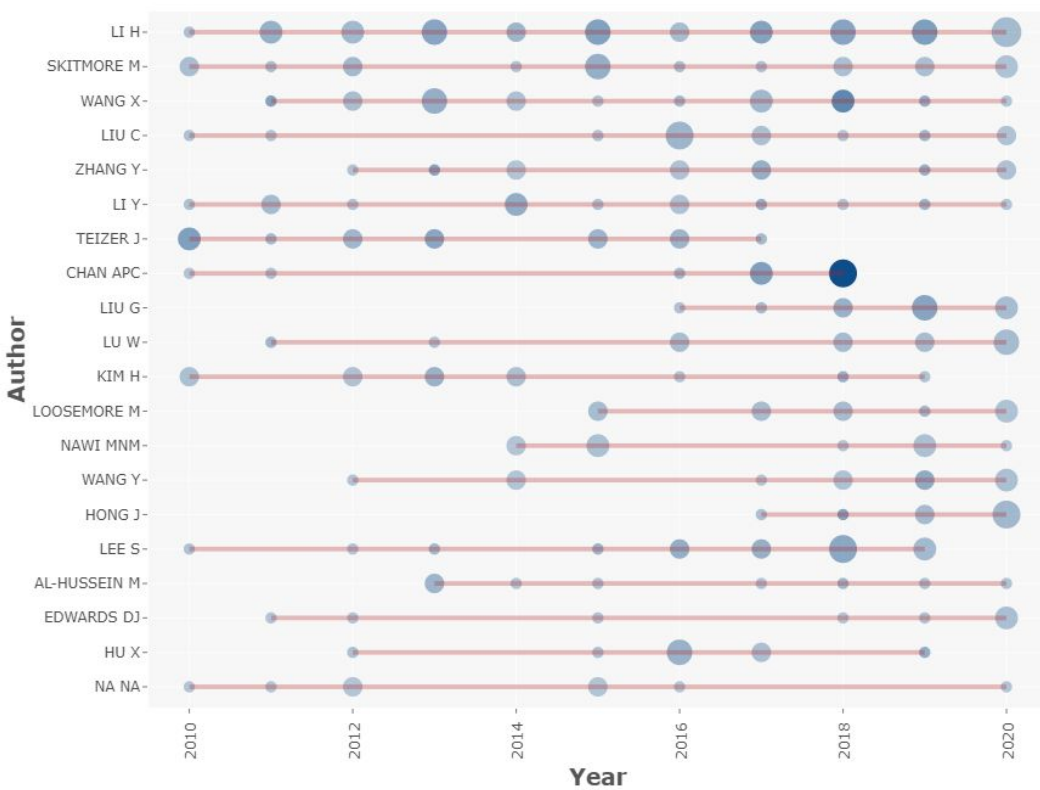

Figure 7: Top authors production over time

11 articles. Figure 7~~6~~ presents the production trends and consistency of the authors. : LI, H. appears to be the most consistent authors over the years, followed by SKITMORE, M and LI, Y.

6 Network analysis and trend word analysis.

6.1 *DT trend topics*

This refers to topics or areas of focus in construction DT. This section identifies these words and the year they became a topic of interest in the construction industry. These topics become popular as many researchers publish to understand and apply them to the construction industry. Figure 8 ~~7~~ and Table 4~~3~~ presents these DT related keywords against the year and frequency of occurrence in the construction DT research.

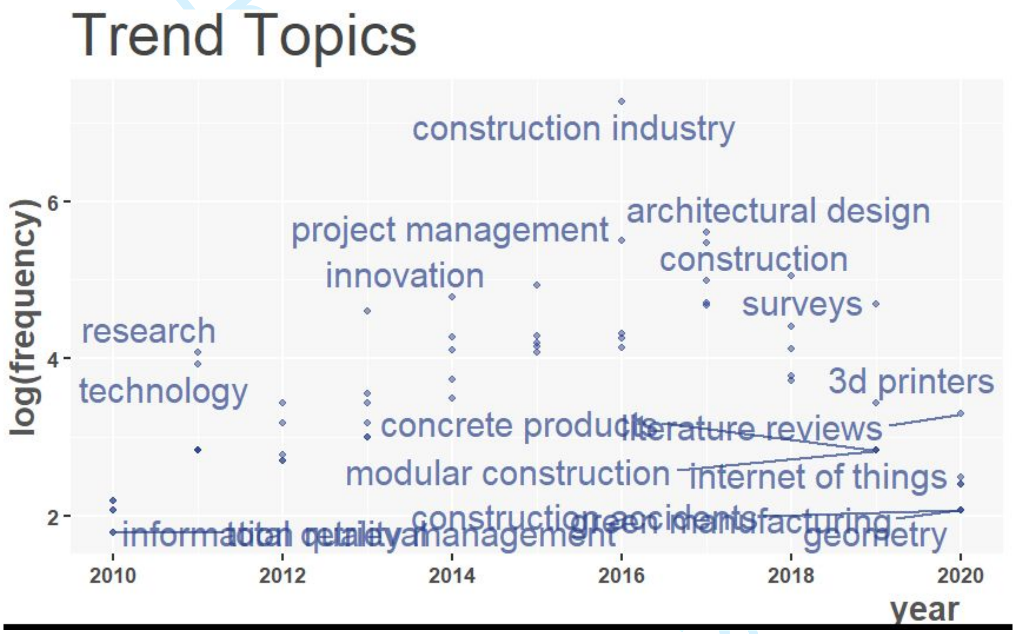

Figure 8: Construction DT trend topics

Table 4: DT trend words

Item	Freq	Year	Item	Freq	Year
Building information modelling	9	2010	Information and communication technologies	42	2014
New technologies	8	2010	Energy utilization	63	2016
Technological forecasting	8	2010	Sustainable development	148	2017
Technology	51	2011	Internet of things	17	2019
Three dimensional	17	2011	Modular construction	17	2019
Computer simulation	16	2012	3d printers	31	2019
Information technology	100	2013	Industry 4.0	12	2020
Radio frequency identification (rfid)	31	2013	Learning systems	11	2020
Information systems	24	2013	Green manufacturing	8	2020
Innovation	120	2014			

The industry has been discussing sustainable development more, followed by innovation and information technology. The next section is the network analysis of co-occurring words to understand the research directions and map out the clusters. Also, it provides an insight into when these technologies and concepts were introduced into the construction industry research discussions. For instance, BIM was introduced in the year 2010, RFID in the year 2013, among others.

6.2 *Research interests in construction DT.*

This section discusses the different research focuses in construction DT. To achieve this, the study analysed the co-occurrence of keywords (authors and journal indexed) from the data collected using VOS viewer. This approach provides a more balanced and comprehensive pool of keywords than the adoption of authors keywords or journal indexed keywords individually. The study adopted a minimum occurrence of 5 for the keywords; this produced a total link strength of 68436, 6 clusters and a total of 793 keywords. These keywords were clustered through association hence we have 6 clusters. The clusters are consequently named and discussed in light of the different aspects of DT as identified in (Verhoef et al. 2021). Figure 9 presents the co-occurrence map, and the list of keywords in each cluster are presented in the appendix.

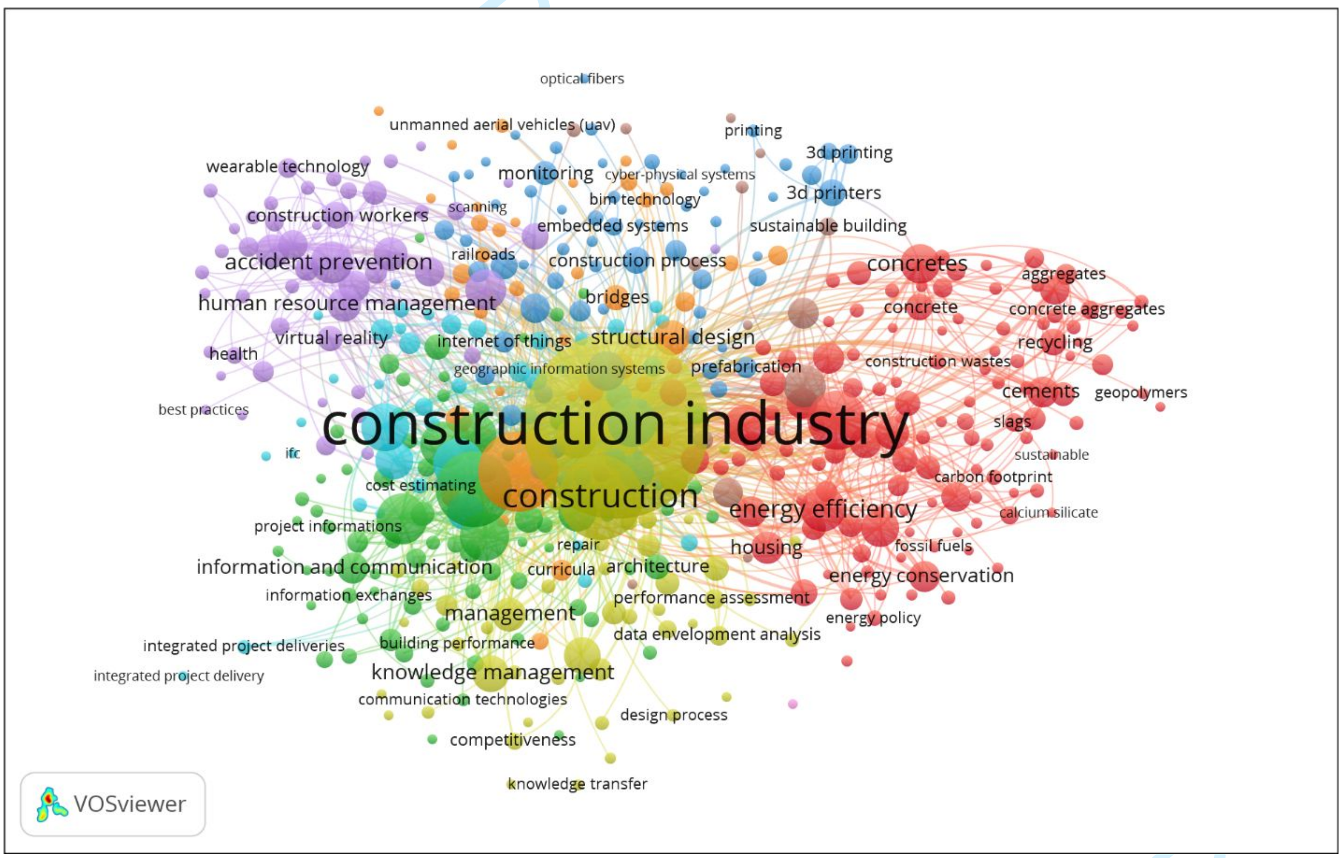

Figure 9: Research focus network visualisation

Cluster 1 **(Organisational change management)**

This cluster (red region) can be said to be the organisational change management and challenges faced by construction organisations due to the introduction of technologies. The cluster also identifies three aspects of DT, which are technology, organisational behaviour and construction project aspects. The technologies in the cluster are blockchain, green building technologies, cloud computing and ICT. The technologies disrupt the way things are done in organisations and on projects. For instance, blockchain technology is a decentralised system for making transactions hence remove unnecessary bottlenecks and intermediaries. Adopting blockchain technology in the construction industry ensures a more open process and increases confidence among the project parties. According to (Kassem, Lia, and Greenwood 2018), it reduces human error, makes traceability of transactions possible. Blockchain technology can be applied in BIM, intelligent transport, smart cities (Kassem et al. 2018), construction supply chain (Wang *et al.*, 2017). DT as an external force causes structural changes in organisations and informs survival strategies (Cameron and Green 2009; Matt et al. 2015). Some strategies identified are inter-firm collaborations to help construction organisations survive the disruptive effects of DT.

Furthermore, DT enables dynamic capabilities in organisations and ensures competitive advantages(Teece 2018; Teece, Pisano, and Shuen 1997). From the preceding, the three aspects in this cluster affect the final project outcome. Although it disrupts the existing system and workflow, it, however, adds value to the construction industry. Summarily, it can be said that these technologies bring organisational change management, affect organisational structure and cultures. It also makes organisations develop strategies for survival in the digital-driven world and consequently affects all construction stakeholders, affects the supply chain and improves the project management process.

Cluster 2 **(Technology, project and sustainability)**

Although concrete is widely used in construction, it has been observed that despite its advantages, it is laden with several challenges, among which is the contribution to the global CO_2 output, labour intensive, health implications for workers (Bos et al. 2016) among others. Cluster 2 (lime green) addresses the technology, project and sustainability aspects of DT. The technology identified in this cluster is additive technology which 3D printing is one of the methods. 3D printing has been in use in the construction of concrete since the mid-1990s and possesses the potential to address the challenges of the traditional concrete production method(Bos et al. 2016). Some of the inherent benefits in additive manufacturing for the construction industry include reduction of construction material waste (Hossain et al. 2020), use of multiple materials (Delgado Camacho et al. 2018) which will encourage the optimal use of materials, and also provide design freedom and encourage automation of the construction process (Paolini, Kollmannsberger, and Rank 2019). 3D printing in construction also possesses the advantage of solving the labor shortage being experienced in the construction industry in some parts of the globe(Hossain et al. 2020). Despite the identified benefits of 3D printing in the construction industry, its large scale adoption has been hampered by the huge infrastructural costs (Hossain et al. 2020) required by stakeholders.

Cluster 3 **(technology, data exchange and application)**

The colour green indicates this cluster on the network visualisation. The three classifications of keywords are technology, data exchange and application aspects. The technology in this cluster is BIM and CAD. The other aspects are data management and sharing and the applications of BIM in the construction industry. BIM has been described as a revolutionary technology in the construction industry and it is used in conjunction with other technologies to achieve many benefits for the construction industry. ~~Ge *et al.* (~~Ge et al. (2017) through a case study demonstrated that BIM provides accurate estimations of deconstruction materials and improves waste management. Thus it is useful in every aspect of the building lifecycle from planning to demolition. The widespread adoption of BIM especially in developing countries, has been observed to suffer set-backs due to some barriers – cultural, educational, infrastructural, policy and transparency(Adekunle, Aigbavboa, and Ejohwomu 2020). However, the developing countries ~~has~~ have been achieving good adoption rates recently despite the hurdles (Adekunle et al. 2021). Thus it can be inferred that despite the study of Jung and Lee (Jung and Lee 2015) indicating a wide difference in the adoption rates across continents, this has changed. Although the present adoption rate across continents, developed and developing countries is lacking.

Cluster 4**(artificial intelligence, big data, virtual reality and wearable technology)**

This is shaded in yellow on the network visualisation. This cluster, unlike the previous ones, has only two aspects which are technology and applications. The technology identified in this cluster are artificial intelligence, big data, virtual reality and wearable technology. Wearable technologies in the construction industry include smart vests and wristbands (Choi, Hwang, and Lee 2017). The application identified in this cluster is mainly on construction health and safety. The adoption of virtual reality and wearable technologies has been shown to prevent accidents, promote and improve construction safety (AL-Sahar, Przegalińska, and Krzemiński 2021; Frank Moore and Gheisari 2019; Zhao and Lucas 2015). Connectivity has been identified as a barrier to the adoption of big data applications in the construction industry (Hedges 2012). In order to aid the adoption of Big data, (Martínez et al. 2021) developed and validated models necessary for the easy adoption of big data. The developed model identified, described and established the relationships between the elements of the model architecture. Similarly, ~~Bilal et al (~~Bilal et al. (2016) proposed a big data ~~arichiteture~~ architecture for construction waste analytics. Exploring big data in the construction industry presents a process improvement goldmine. This is due to the huge data generating nature of the construction industry.

Cluster 5 **(Internet of things (IoT) and Cyber-physical systems (CPS) and construction project)**

The colour purple indicates this cluster. The cluster has three aspects, namely, technology, benefits and construction project aspects. The technology identified in this cluster are the

Internet of things (IoT) and Cyber-physical systems (CPS). IoT as a standalone technology or when used in combination with other emerging technologies in the construction industry, enhances construction productivity (Heiskanen 2017) in prefabrication~~,~~ and modular construction (C. Z. Li et al. 2018; Zhao, Liu, and Mbachu 2019; Zhong et al. 2017) and CPS employed for real-time monitoring (Liu et al. 2020). These technologies, through their various uses, enhance productivity and ensure quality assurance. These technologies are also integrated with BIM to achieve better process improvement and efficiency. For instance, building information modelling and Intern~~a~~et of things (Tang et al. 2019).

Cluster 6 (underground construction and technology)

This cluster is indicated in blue colour. This cluster contains three aspects which are technology, construction projects and application aspects. However, the application identified in this cluster is for underground construction; this includes the construction of passageways, tunnels among others, underground. Laser scanning is a useful and potent tool for ~~the construction and maintenance management of~~constructing and maintaining tunnels(Wang et al. 2014). Other technologies in this cluster are RFID, robotics, wireless sensor networks, and unmanned aerial systems. These technologies are useful for different stages of the construction project, from planning and design, construction, commission and operation and commission. The uses include information management and traceability, 3D printing, prefabrication of building components, aerial survey and progress monitoring, safety inspection, building maintenance (Davila Delgado et al. 2019; Lu, Huang, and Li 2011; Martinez et al. 2021; Tatum and Liu 2017; Zhou and Gheisari 2018).

A critical study of the clusters mentioned above gleaned from the bibliometric data suggests that the DT discussion in the construction industry goes beyond the proposed scope (Verhoef et al. 2021). Hence the study ~~comes up with~~developed a flow model (Figure 10) for DT discussion in the construction industry.

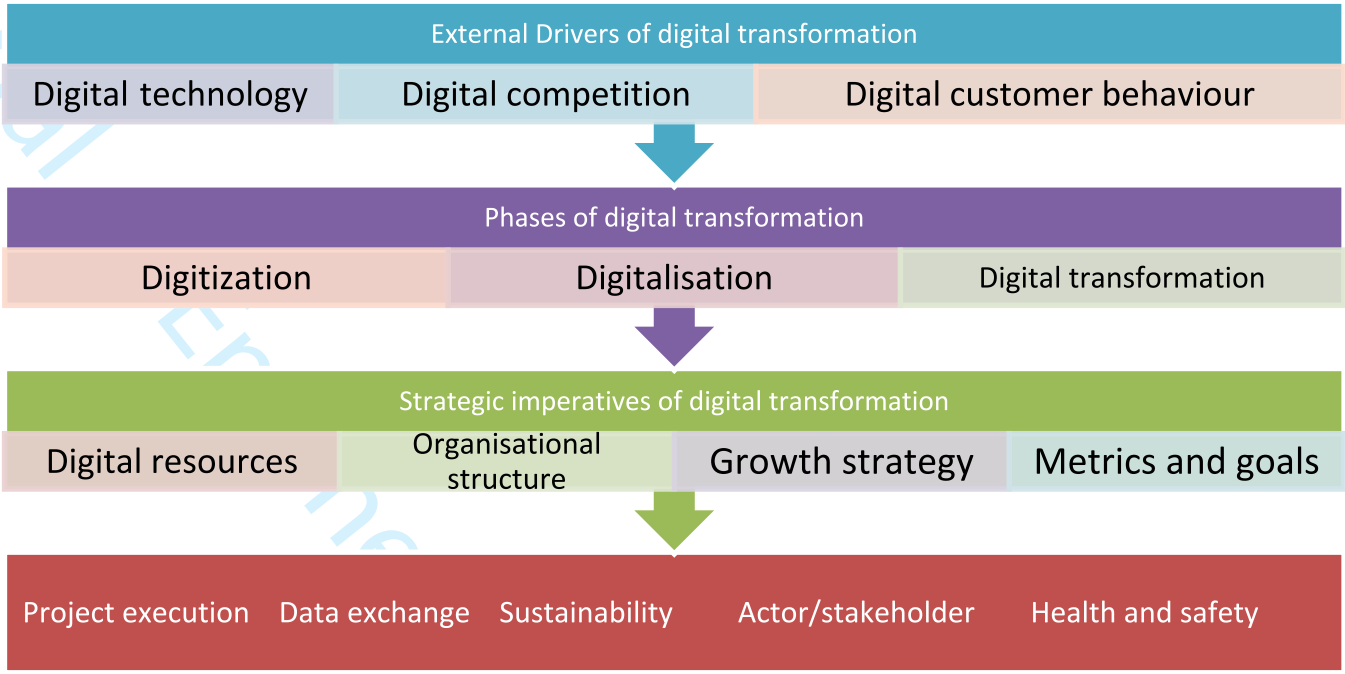

Figure 10: Flow model for construction DT

The DT in the construction industry spans organisational, project, stakeholder and the environment.

7 Future directions and trends for DT in construction

The section discusses the future trends in construction DT. This is achieved through the analysis of keywords using the network visualisation map in VOSviewer. This map, unlike the network visualisation map, includes a time bar showing the years in corresponding numbers to different clusters on the map. From figure 11, the area for future research referred to here as the colour red indicates hot topics. The budding technologies identified for future research and full integration into the construction industry processes are blockchain technology, cloud computing, green building technology, 3D printing, digital fabrication, wearable technologies, CPS, IoT, wireless sensor networks, and unmanned aerial systems.

Meanwhile, organisations are to focus on change management in response to the external force of DT; there is also a need for more focus on small to medium-sized organisations adoption and response to DT, inter-firm collaborations and mergers in response to DT, the impact and response of organisational culture and structures to DT requires more research in the construction industry.

Furthermore, the use of DT in facilities management cost estimating and quality assurance in construction. The impact of DT on project success, project teams and stakeholders and offsite construction. Research is also required on the use of DT on energy consumption and performance, energy-saving and use, environmental regulations and renewable energy sources for the construction industry. Figure 12 shows an overview of the research focus and the areas of future directions for construction DT.

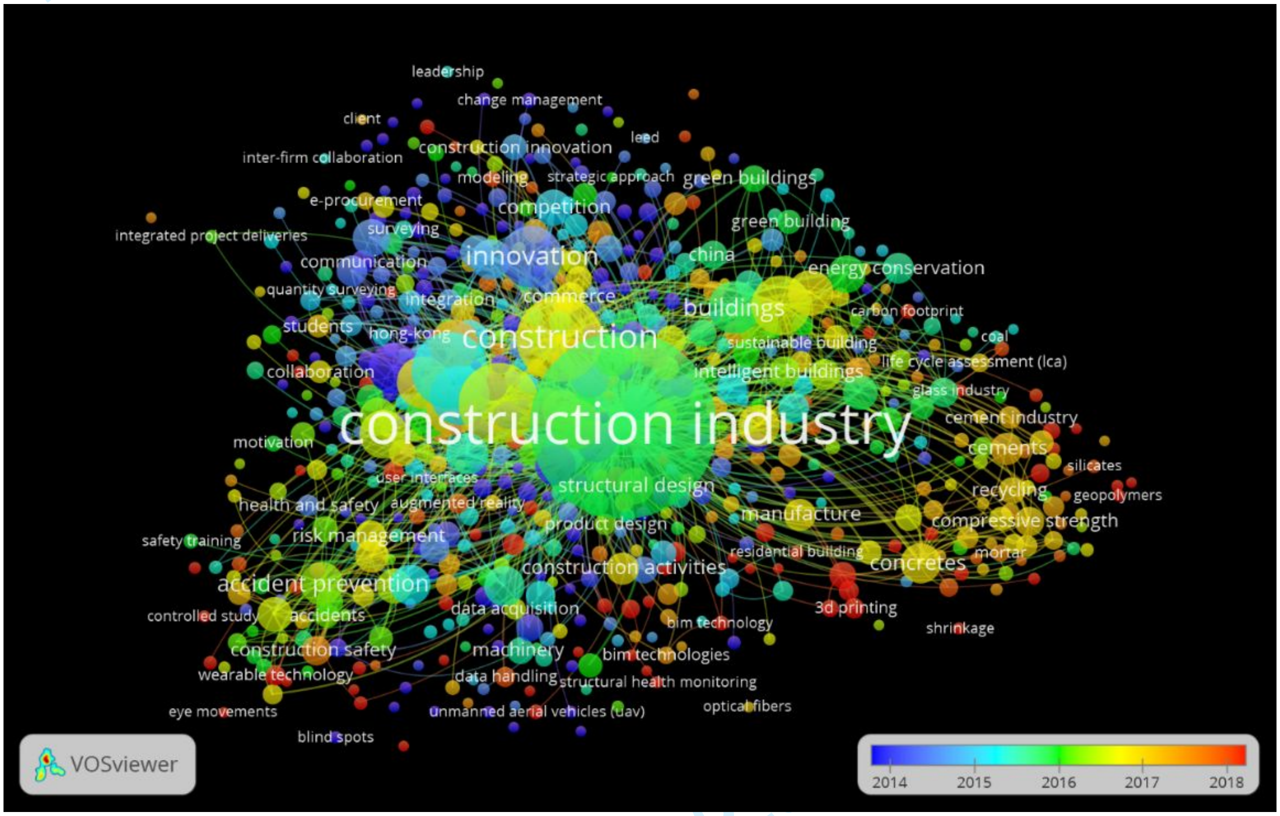

Figure 11: Overlay visualisation

8 Conclusion

The digit~~i~~al transformation revolution is changing every sector greatly and making them become more productive and efficient. Unlike other industries, the construction industry has always been notorious for late transformation technologically. This tradition~~,~~ has been found to be counter productive and there have been several studies and efforts to understand and counter this. This is due to the inherent benefits in these ~~transfromations~~transformations. In order to understand and establish the scorecard of the construction industry in the present digital transformation era, the study reviewed the DT journey in the AECO sector between 2010-2020 and identified the different aspects of DT in the AECO sector.

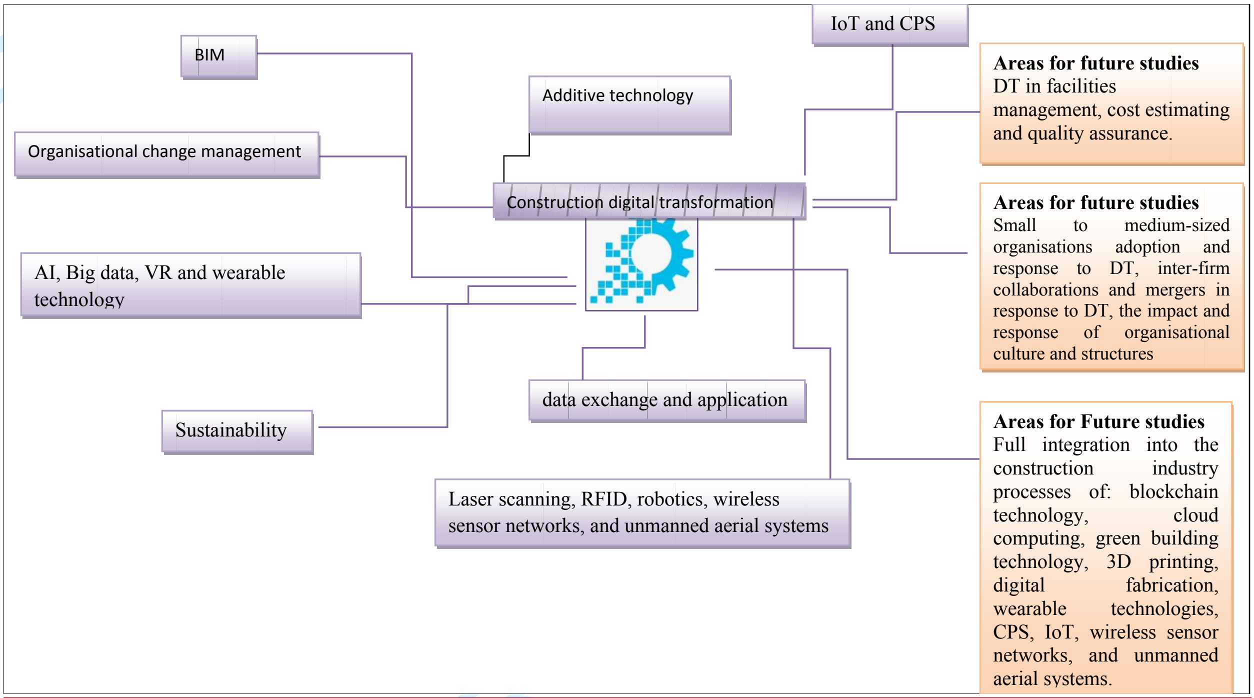

Figure 12:Research focus and areas for future study

The study results demonstrate, among other findings, the following:

1. This study was able to show that DT is beyond the technologies as it affects different aspects of the industry. It articulates the DT developments in the AECO sector and provides an outlook on the future research areas in the sector.
2. The study identified the different aspects of DT in the AECO sector. Furthermore, building on the existing flow model of DT discussion, the study developed a flow model for the discussion of DT in the construction industry.
3. For the past decade, the construction industry has focused more on BIM implementation. However, recent digital transformation efforts in the construction industry has have witnessed the integration of emergent technologies with BIM and the construction process.
4. The digital transformation discusses in the construction industry consists of different phases and aspects. This makes it different from other industries. This also gives credence to the peculiarity of the construction industry and it, by extension, means more efforts are needed to achieve digitial transformation in the construction industry.

The study findings are important as they demonstrate that the construction industry unlike in the previous technological transformation eras, have been very active in the area of digital transformation in the last decade. It provides a basis for the digital transformation researhce research in the construction industry. This study has both research and practical implication; however, it has some shortcomings as it gathered data from the SCOPUS database; thus, other databases were not considered.

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Appendix

Cluster 1

Technology			Organisation			Project		
keyword	Freq	total link strength	keyword	Freq	total link strength	keyword	Freq	total link strength
Blockchain	9	32	Change management	9	47	Building performance	8	35
Cloud computing	8	56	Competitive advantage	21	138	Construction stakeholders	9	52
Digital technologies	15	93	Competitiveness	13	59	Construction supply chain	15	124
Digitalization	6	11	Inter-firm collaboration	5	23	Environmental sustainability	9	75
Green building technologies	5	37	Knowledge sharing	10	40	Facilities management	5	32
ICT	14	65	Organizational culture	8	37	Procurement	11	67
Information and communication technologies	40	287	Organizational innovation	5	26	Project management	236	1571
			Organizational performance	5	25	Project success	5	15
			Organizational structures	8	48	Project team	13	89
			Small to medium-sized enterprises	5	19			

Cluster 2

Technology			Project			Sustainability		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
3-d printing	13	100	Construction and demolition waste	10	79	Eco-design	6	69
3d printers	29	194	Construction material	6	60	Emission control	24	239
3d printing	16	113	Construction waste	7	51	Energy	6	33
Additive manufacturing	16	95	Construction wastes	10	93	Energy conservation	38	302
Digital fabrication	8	41	Glass fibers	5	27	Energy consumption	5	50
Energy efficient technology	5	47	Retrofitting	6	51	Energy dissipation	5	34
Energy-saving technologies	6	51				Energy efficiency	82	590
Green manufacturing	8	67				Energy performance	5	31
Green technology	6	41				Energy policy	10	111
Nanotechnology	7	17				Environmental pollutions	5	43
Microstructure	5	33				Energy saving	6	36
Scanning electron microscopy	9	54				Energy use	7	67
						Environmental protection	13	116
						Environmental regulations	5	51
						Gas emissions	19	176
						Green building	23	142
						Green construction	6	39
						Greenhouse gases	26	271
						Renewable energy resources	8	91

Sustainable construction	30	185
Sustainable development	139	1112
Thermal insulation	10	67

Cluster 3

Technology			Data exchange			Applications		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
3d modeling	7	76	IFC	5	28	Quality control	22	168
BIM	106	535	Industry foundation classes - IFC	8	77	Scheduling	15	127
Building information model - BIM	95	780	Information analysis	8	79	Facility management	6	49
Building information modeling	59	390	Information exchanges	10	85	Architectural design	255	1906
Building information modeling (BIM	30	200	Information modeling	5	32	Cost benefit analysis	33	290
Building technologies	9	63	Information sharing	6	55	Cost estimating	10	99
Computer aided design	26	208	Data acquisition	19	142	Design and construction	20	142
Information technologies	20	172	Data visualization	11	120	Simulation	20	135
			Interoperability	11	101	Three dimensional computer graphics	18	157

Cluster 4

Applications			Technology		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
Accident prevention	73	591	Artificial intelligence	12	83
Ergonomics	10	84	Big data	9	45
Hazard identification	8	62	Deep learning	5	24
Health and safety	20	118	Knowledge based systems	17	138
Image processing	5	32	Neural networks	11	76
Occupational accident	9	80	Virtual reality	27	202
Occupational health and safety	5	44	Wearable technology	17	121
Occupational risks	49	410			
Occupational safety	14	138			
Protective clothing	6	53			
Safety engineering	25	218			
Safety management	19	147			
Safety performance	12	79			

Cluster 5

Technology			Benefits			Construction project		
Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq	Total link strength
Cyber physical system	7	65	Quality assurance	5	41	Construction productivity	12	80
Cyber-physical systems	5	30	Real time monitoring	7	41	Construction quality	6	50
Cyber-physical systems (cps)	5	48	Standardization	11	69	Lean construction	19	132
Internet of things	18	113				Lean production	12	83
Internet of things (IOT)	10	70				Modular construction	18	105
						Off-site construction	7	46
						Off-site manufacturing	5	24
						Offsite construction	5	33
						Prefabricated construction	14	112
						Prefabrication	18	92
						Productivity improvements	12	86

Cluster 6

Keyword	Freq	Total link strength	Keyword	Freq	Total link strength	Keyword	Freq
Laser applications	13	101	Construction planning	10	66	Underground construction	7
Laser scanning	9	68	Life-cycle management	5	38		
Radio frequency identification	5	51	Resource allocation	6	39		
Radio frequency identification (RFID)	31	256					
Radio frequency identification technology	6	55					
Real-time information	8	85					
Remote sensing	6	44					
RFID	12	101					
RFID technology	5	41					
Robotics	20	104					
Sensors	7	41					
Unmanned aerial systems	5	31					
Wireless sensor networks	5	46					

The research search string

TITLE-ABS-KEY("construction industry" AND "technology" OR "Innovation" OR "industrial revolution" OR "Digitisation") AND (EXCLUDE (PUBYEAR,2021)) AND (LIMIT-TO (SUBJAREA,"ENGI")) AND (LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011) OR LIMIT-TO (PUBYEAR,2010)) AND (LIMIT-TO (DOCTYPE,"ar"))