

Research focus for construction robotics and human-robot teams towards resilience in construction: scientometric review

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Abstract

Purpose – Rapid urbanisation and recent shock events have reiterated the need for resilient infrastructure, as seen in the pandemic. Yet, knowledge gaps in construction robotics and human-robot teams (HRTs) research limit maximising these emerging technologies' potentials. This paper aims to review the state of the art of research in this area to identify future research directions in HRTs able to aid the resilience and responsiveness of the architecture, engineering and construction (AEC) sector.

Design/methodology/approach – A total of 71 peer-reviewed journal articles centred on robotics and HRTs were reviewed through a quantitative approach using scientometric techniques using Gephi and VOSviewer. Research focus deductions were made through bibliometric analysis and co-occurrence analysis of reviewed publications.

Findings – This study revealed sparse and small research output in this area, indicating immense research potential. Existing clusters signifying the need for further studies are on automation in construction, human-robot teaming, safety in robotics and robotic designs. Key publication outlets and construction robotics contribution towards the built environment's resilience are discussed.

Practical implications – The identified gaps in the thematic areas illustrate priorities for future research focus. It raises awareness on human factors in collaborative robots and potential design needs for construction resilience.

Originality/value – Rapid urbanisation and recent shock events have reiterated the need for resilient infrastructure, as seen in the pandemic. Yet, knowledge gaps in construction robotics and HRTs research limit maximising these emerging technologies' potentials. This paper aims to review the state of the art of research in this area to identify future research directions in HRTs able to aid the resilience and responsiveness of the AEC sector.

Keywords Human-robot collaboration, Construction robotics, Human-robot teams, Research focus, Scientometric review, Ergonomics in robotics

Paper type Literature review



Introduction

Diverse workforce-related challenges and productivity issues are currently a dilemma in the construction industry, partly because of its heavy dependence on human tasks, which are often debilitated by a shortage of skilled labour, high incidence of safety risks, potential accidents/injuries, time constraint, location and safety factors (Eiris and Gheisari, 2017; Bryan and Mahya, 2021). Emerging Industry 4.0 innovations, such as the use of virtual human applications in AEC (Eiris and Gheisari, 2017), remotely piloted aircraft for damage detection, health and safety and site monitoring, amongst others (Golizadeh *et al.*, 2019), digital twin for optimising construction data (Liu *et al.*, 2021a, 2021b, 2021c), cyber-physical systems, robotics and collaborative robots have provided an opportunity for a better-enhanced construction environment. Robotics have been identified as central to augmenting debilitating productivity issues associated to workers and retool conventional workflow techniques in the construction workplace (Bryan and Mahya, 2021). However, what this means in real terms is sketchy and still taking form. Heavy concerns on the implications of autonomous robots on construction sites have generated socio-cultural and economic debates, raising issues on the form of intervention robots would have and what this connotes; lesser human workers on sites or no human workers on sites. To resolve some of these agitations and concerns, innovations are geared towards robots collaborating with humans instead of outright autonomy of robots on sites. This has been suggested to enable robotics to be more socially sustainable and technically productive, lower construction costs through waste reduction (Mahbub, 2015), ensure safer workplaces (Fischer *et al.*, 2020) and deliver resilient and responsive infrastructure.

Human-robot teams (HRTs) aim to improve construction productivity and resolve work-related challenges through human-robot collaboration (HRC). While HRTs research is an emerging area, it holds vital benefits. It plays a crucial role in the fourth industrial revolution through the “use of collaborative robots” (or “cobots”), which are primarily designed as team robots to share tasks with humans. They are highly beneficial in increasing worksite safety by reducing overexertion, which reduces fatigue and accidents common amongst workers (Bryan and Mahya, 2021), enhance team performance leading to more productivity as they are easy to train (Calitz *et al.*, 2017), speed up construction processes, reduce lifecycle cost and improve designs.

These potential benefits have aroused an increasing level of interest and concerns (Hancock *et al.*, 2011), especially regarding the art of safety and ergonomics (Gualtieri *et al.*, 2021). To improve their contribution towards resilience, procedures to incorporate cobots and robotics in HRTs (Bryan and Mahya, 2021), barriers to their adoption (Mahbub, 2015), trust amongst HRTs (Hancock *et al.*, 2011), their use in the future workplace (Calitz *et al.*, 2017) and social robots in HRTs and HRTs in organisations (Wolf, 2020) are grey areas to build knowledge for effective adoption. Given this level of interest and need for more research advancement in HRTs and robotics, a critical review of the extant literature is imperative to establish the direction of research for successful implementation of HRTs and robotics in the construction jobsite and academic learning (Gualtieri *et al.*, 2021). Existing review studies on robotics and HRTs such as Gualtieri *et al.* (2021) are limited to ergonomics, whereas Aghimien *et al.* (2019) are limited to robotics and automation. While these works are valuable to the body of knowledge, it is imperative to avail a comprehensive outlook of emerging research on the topic, outstanding research themes, the geographical distribution of active researchers and consequently aggregate a research direction for further studies through a quantitative approach at acutely dissecting the state of the art of HRTs/robotics in the architecture, engineering and construction sector. Therefore, to successfully drive research in HRTs/robotics, this study aims to broadly map the scope and trends of the

extant literature on HRTs/robotics in the architecture, engineering and construction sector and highlight key thematic areas for future studies in HRTs. It is envisioned that the study would serve as a pedestal to drive further ground-breaking studies and serve as a catalyst for more scholarly research themes to better pave the way for the use of HRTs/robotics towards a resilient construction sector.

Theoretical background

Human–robot teams in the construction industry

According to [Perez et al. \(2018\)](#), robotics hugely re-invent the shop floor of manufacturing companies and the fourth industrial revolution ([Aghimien et al., 2019](#)). Collaborative robots or cobots are designed to work with humans and can be easily trained on tasks ([Afsari and Afkhamiaghda, 2020](#)). HRTs studies are an emerging interdisciplinary field that falls within a broader scope of human–robot interaction (HTI) ([Follini et al., 2021](#)). Since the 1970s when robotics was first introduced into the construction industry for prefabrication in Japan ([Afsari et al., 2018](#)), they have evolved rather much slowly ([Delgado et al., 2019](#)) compared to the manufacturing industry.

While the adoption has evolved slowly, studies are instructive as [Akinradewo et al. \(2021\)](#) posit robotics enhances accuracy through the use of lasers for analysis of dimensions, standardised methods to design specifications, effective lifecycle cost, improved working conditions and waste reduction. The HRT/robotics research area is growing; studies across a wide range have focused on sustainability, prefabrication, trust, safety, ergonomics, HTI and artificial intelligence. [Liu et al. \(2021a, 2021b, 2021c\)](#) proposed a framework of worker-centred collaboration that enables robots to capture workers' brainwaves from wearable electroencephalographs, measure their task-related cognitive load and adjust the robotic performance accordingly. [Pan et al. \(2020a, 2020b\)](#) established a framework for using robotics in a sustainable building; [Perez et al. \(2018\)](#) investigated robotics and augmented artificial intelligence. A new pathway has also been charted in using tower construction to examine the collaboration between a robot and groups of people in providing behavioural insights of humans around robots, as cost efficiency is imperative in adoption; studies have also examined guidelines for developing future HRTs economically ([Akshatha et al., 2017](#)). [Bugmann et al. \(2011\)](#) assessed the designs of cobots in using sustainable resources, [Linner et al. \(2020\)](#) structured the context for collaborative robots using an integrated scenario approach, whereas [Liu et al. \(2021a, 2021b, 2021c\)](#) further evaluated a human-centred collaborative framework that captures the brainwaves of workers using wearable electroencephalograph to study the robot's performance.

[Wolf \(2020\)](#) identified HRT types as: Autonomous mixed team, human-/robot-directed mixed team, robot-directed human team and human-directed team. In an autonomous mixed team, collaborative work is executed between robots and humans in a shared space on the same tasks. In the human–robot-directed mixed team, workers perform tasks in coordination with robotic partners ([Wolf and Stock-Homburg, 2020](#)). A robot-directed human team involves a robot led coordination of tasks, and human-directed teams advocate an individual human worker supervising operations of robots ([Wolf and Stock-Homburg, 2020](#)). However, safety issues are central in these forms of collaboration; productivity is the goal and ultimately enables a safe working environment. Immense scrutiny is imperative in ensuring zero accidents with human users. As highlighted by [Salmi et al. \(2018\)](#), the traditional solution to ensuring safety between human workers and robotic systems in an industrial robot system is to keep users and autonomous robots away from each other. With the increasing innovation for a fenceless collaborative approach between humans and robots, safety standards such as the European robot standard (EN 775:1992) and ISO 10218-

1:2006 have to be continually reviewed in keeping up with innovations around HRTs and specifically to have a widely accepted standard for the construction industry. Besides from safety issues, the adoption of construction robotics on the site is debilitated by issues such as complexity and uniqueness of projects on the site, task sequence, varying construction processes, inaccuracies of components buildings and designs (Bryan and Mahya, 2021). Furthermore, they are impacted by issues such as the rigid movement of robots and the edges in robots design with increasing need to have smooth or round edges (Salmi *et al.*, 2018). The need to adapt to gesture, effectively allocate tasks, integration of robots into teams, switching of roles, training and perception of collaborative robots by human workers are critical in the successful implementation of HRTs/collaborative robots in the architectural, engineering and construction sector (Dobra and Dhir, 2020).

Research methodology

This study adopted a quantitative approach using scientometric techniques to analyse, visualise and review the predefined objectives for the research. The choice of technique was adopted to generate clusters, thematic areas and trends with descriptive illustrations and charts. The scientometric approach has been adopted in another review of emerging innovations in the construction industry such as scientometric analysis of remotely piloted aircrafts (Golizadeh *et al.*, 2019), scientometric analysis of building information modelling (BIM) (Saka and Chan, 2019a, 2019b), use of a bibliometric review in examining green buildings research (Olawumi *et al.*, 2017), a bibliometric analysis of construction automation and robotics in construction (Aghimien *et al.*, 2019).

Scientometric review

According to Saka and Chan (2019a, 2019b), a scientometric review uses analysis and visualisation of academic literature to avail the evolution of research in an academic field. Other approaches are a bibliometric review (Olawumi *et al.*, 2017) or a systematic literature review (Eiris and Gheisari, 2017). Network analysis uses enhanced procedures and tools using algorithms derived from network theory and improved through the advent and improved use of the internet and computers to scientifically highlight the strength of social network impact in research and research trends (Babalola *et al.*, 2021). There are several software packages for analysing scientometric research: VOSviewer, BibExcel, CiteSpace, CoPalRed, Sci2 and VantagePoint (Golizadeh *et al.*, 2019). There is also increasing use of “publish or perish” scientific repository in analysing academic papers (Cardoso *et al.*, 2020). VOSviewer software has gained more significance and enhanced usage among construction management researchers in the industry, especially in graphical and metadata metric studies, for example, Olawumi *et al.* (2017); Aghimien *et al.* (2019); Saka and Chan (2019a, 2019b); Golizadeh *et al.* (2019); and Babalola *et al.* (2021).

What distinguishes VOSviewer and makes it popular could be attributed to its capability of using different databases in the same study (Saka and Chan, 2019a, 2019b; Babalola *et al.*, 2021); it is open source, user friendly and able to visualise comparisons, connections, interactions and networks among bibliographic data through the demonstration of visually understandable, aesthetically pleasing and interpretable bibliometric graphs and maps. Furthermore, its strength is pronounced in displaying large networks in a recognisable pattern (Babalola *et al.*, 2021), conducting the required analyses from a data set, developing a bibliometric map and further delivering these results accurately and promptly. The fluidity and flexibility in re-testing the results to ensure validity highlights these approaches as scientifically imperative in confirming results.

VOSviewer and Gephi were adopted in this study for analysis because of their features, high rate of adoption in academic review and ease of use (Wen and Gheisari, 2020; Babalola *et al.*, 2021; Mariam *et al.*, 2021). VOSviewer avails analysis through full counting methodology and fractional counting methodology for visualising networks of documents (Jin *et al.*, 2018). For this study, fractional counting methodology to generate author network, co-citation network (co-author citation and document citation) and co-occurring keywords citation were adopted. Gephi is a leading graph visualisation and Java-based exploration software. It is open source, free and useful for social network analysis (Golizadeh *et al.*, 2019). The scientometric review process is illustrated in Figure 1.

Data retrieval

Various digital databases exist in scientometric analysis, such as Google Scholar, ISI Web of Science and Scopus, most commonly used for scientific inquiries. As stated by Olawumi *et al.* (2017), there is no clear difference in Scopus and Web of Science databases on science-based publications. However, there is a substantial overlap in their records. While Google Scholar has been found to possess in its repository a more extensive collection of publications than both Scopus and Web of Science, its demerits lie in attributing many incorrect publication attributions, such as an author with the same first initial and last name being attributed more citations. Other limitations with Google Scholar involve indexing articles, as it measures all conference abstracts, which has nothing to do with citations, invariably increasing the numbers of papers astronomically. However, the publications were retrieved within the Scopus database for this study. It has been identified as the major database used by research because of its massive reach of academic literature (Saka and Chan, 2019a, 2019b).

The key search query entered on the Scopus database is: “Human-robot teams” OR “Cobots” OR “Collaborative robots” OR “Robotics” with the year limitation set to ten years (2011–2021). The publications were limited to ten years because of the aim of the paper on highlighting emerging research areas and as stated by Aghimien *et al.* (2019), most current

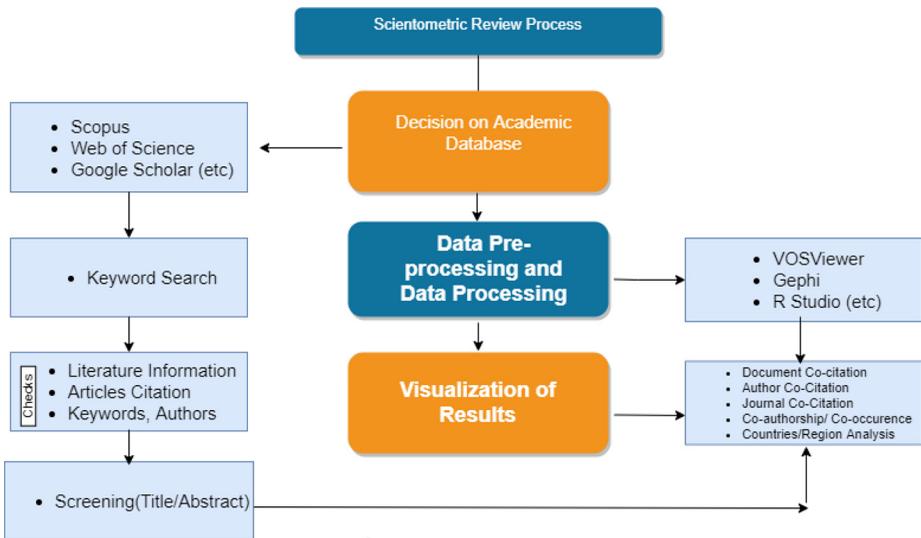


Figure 1.
Scientometric review process

robotics issues emerged in this time frame. The documents were limited to papers published using English as a medium, and territory was left to include all countries. The document type was limited to journal articles. They represent the most influential research studies in scientific mapping because little is gotten from conference papers because of their large numbers and extra amount of complexity it impacts analysis (Zhou and Gheisari, 2018). The document type was refined to publications in engineering, which produced 5,384 documents. It was further refined using the keyword “Construction” to query the “Abstract, Title and Keywords”, which produced a result of 1,483 documents and refined further produce 308 documents. Golizadeh *et al.* (2019) stated that refining the keyword “Construction” still creates some form of ambiguity as it is a relative term applicable in other fields such as manufacturing and the AEC sector. Therefore, abstract filtering of all 308 documents was sighted to refine the data sets to strongly related documents, and studies relating to non-construction sectors were removed. The filtering yielded 71 documents largely on robotics and revealed sparse documents on collaborative teams. While this sample size is relatively small, it is deemed adequate. A previous review by Aghimien *et al.* (2019) included “Automation” in its query and generated more data sets. However, 50 papers for scientometric analysis are well documented in the literature Golizadeh *et al.* (2019) and 32 documents are used in the bibliometric analysis (Mariam *et al.*, 2021).

Results and analysis

Country and regions of publications

Figure 3 shows the distribution of the papers across the countries and regions of the world. Scientific production mapping for countries is imperative in characterising the country's overall performance through articles and author indicators. In this study, the countries with the highest publications are: the USA (26 documents), the UK (5 documents), China (6 documents), Hong Kong (7 documents), South Korea (5 documents), Germany (7 documents), Denmark (3 documents) and Australia (3 documents) with no substantial contribution from Africa. This data is imperative in improving the country's institutional research performance. For instance, the data generated shows that while the study area is emerging, efforts to add knowledge are absent from the African region. This is further instructive in indicating a low network of research collaboration in robotics research between African institutions and developed economies. This could be possibly related to the fact that these institutions in Africa do not view the field of robotics as currently critical in African infrastructure discourse or could be because of the absence of critical infrastructures such as robots, digital skills and technical know-how vital to pushing this level of study within African academia domain. However, in moving with the time, studies in HRTs are important in academia to encourage the financing of projects and increase the productivity of an institution while ensuring academic excellence in contributing to knowledge. Another noteworthy factor is the lack of research funding in most African institutions. Through the increase of research funding to collaborate, access technical know-how and procure hardware and software, institutions can open an opportunity for greater and better research co-authorships (Figure 2).

Visualisation

This section presents the visualisation result for the 71 documents from Scopus using VOSviewer and Gephi. Visualisation entails using software tools for constructing and visualising bibliometric networks such as journals, researchers or individual publications. They can be constructed based on citation, bibliographic coupling, co-citation or co-authorship relations.

Wave of research on construction robotics and human–robot teams

Figure 4 illustrates the number of publications on construction robotics and HRTs within ten years (2021–2011). The first study on construction robotics at the inception of the time frame examined is by Seo *et al.* (2011); it examined the use of task planner design for an automated excavation system and was published in “*Automation in Construction*”. The study developed an excavation task planner to integrate the intelligence of a construction planner and the proficiency of an operator into the automated excavation system’s robotic control mechanism and applied case studies as a research method in the study. Prominent studies in this time frame include Chu *et al.* (2013), who examined robot-based construction automation through applications of a robotic beam assembly system and subsequently developed a robotic transport mechanism that the project’s group will administer (Jung *et al.*, 2013). With 103 citations, Bock (2015) was the most cited publication on construction robotics. The study conducted a past review and future

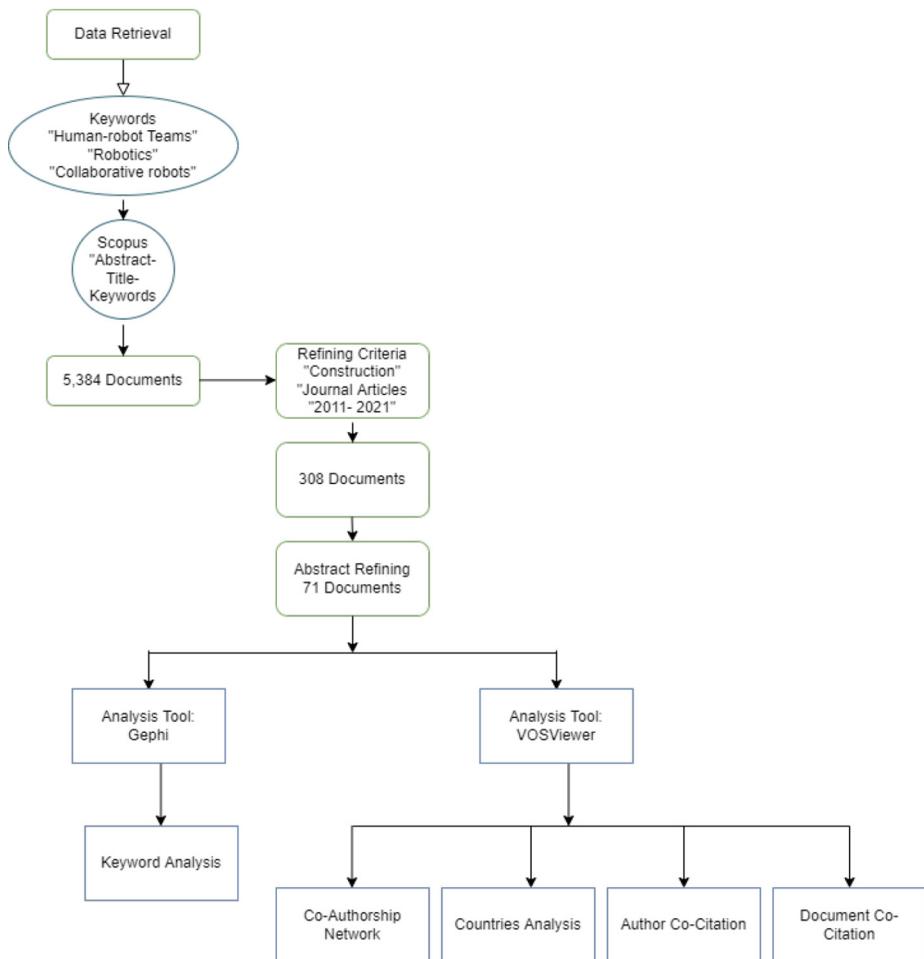


Figure 2.
Outline of research
design

potentials of construction automation and robotics to examine technological disruption and the upcoming ubiquity of robotics. The study identified human factors as critical in collaborating humans with robots on the construction worksite and highlighted five key emerging areas: “robot-oriented design, robotic industrialisation, construction robots, site automation and ambient robotics”. The subsequent trend of the number of publications on construction robotics and HRTs is illustrated in Figure 4, showing a notable steady rate in publications output from 2017 onwards. The sudden increase has also been attributed to emerging interests in construction robotics and HRTs.

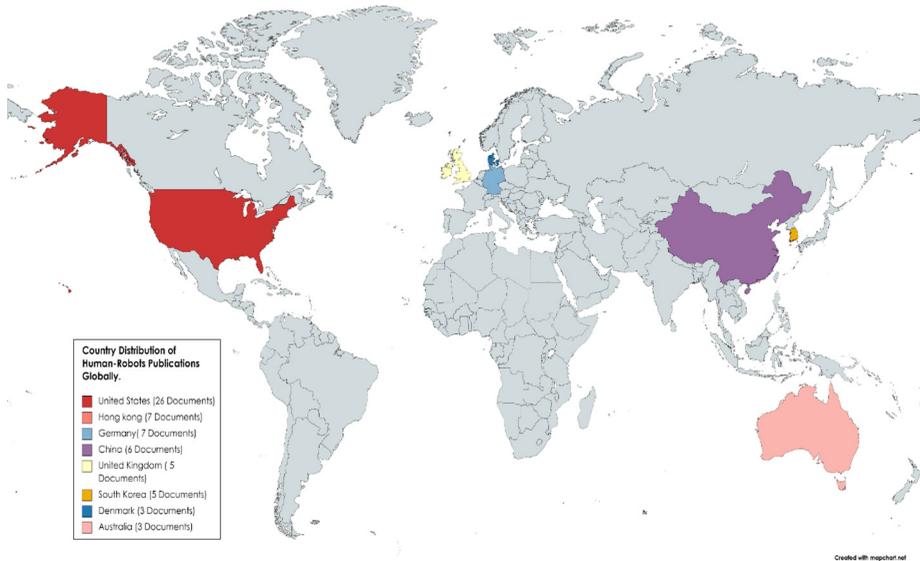


Figure 3. Top countries distribution of human-robot teams globally

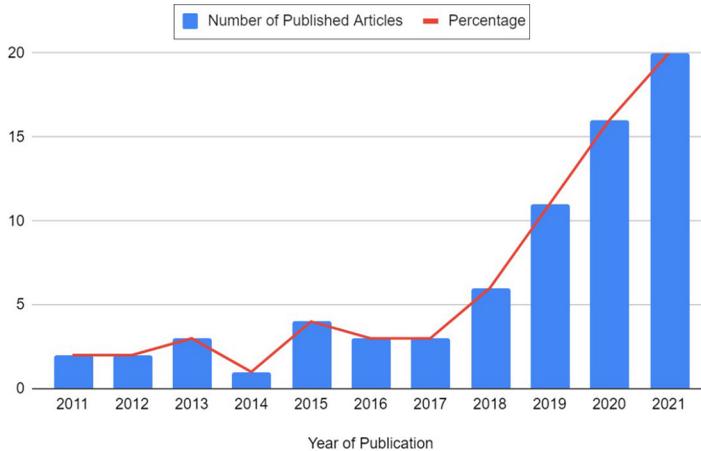


Figure 4. Number of published articles on construction robotics and human-robot teams

Main research areas (co-occurrence of keywords analysis)

Research trends within a domain could be analysed using the trending keywords as they indicate an outlook of the scholarly literature developed within a data set (Su and Lee, 2010). Co-occurring keywords provides a thematic evolution of research in a domain. The network visualisation for co-occurring keywords was analysed using Gephi, Java-based open-source network analysis and visualisation software. The data set from Scopus was categorised to reflect nodes and edges for easy analysis on Gephi. Network analysis in co-occurring keywords depends on linking the weight between two keywords based on the number of publications they occur in (Golizadeh *et al.*, 2019). Using Gephi, comma was used as the separator for the data set. At the same time, the charset was left at the default of UTF-8; both edges table and nodes table were used in the visualisation. An undirected graph method was selected to give a bidirectional relationship between the data sets. Among the nodes, automation, HRTs, safety and robotics design have the highest number of edges. Other prominent edges being robot prefabrication system, robot perception, human-machine interface, Internet of Things (IoT), disorders, exoskeletons, control, autonomous, computer-vision and object identification, etc. Having research areas as the nodes, the visualisation indicated that research interest and focus areas are more concentrated on automation and robot designs, whereas HRTs is an emerging research field. This is supported by Wolf and Stock-Homburg (2020), who identified HRTs as a growing interdisciplinary field. Furthermore, the Gephi visualisation depicting the edges indicates the research interest in HRTs is an offshoot from robotics and other issues surrounding robotics such as safety with robotics, human-machine interface integration, collaborative robots and HRT trust. Also, there is growing interest in exoskeletons as a form of robotics to enhance human performance on tasks.

Clusters of research on construction robotics and human-robot teams

Golizadeh *et al.* (2019) stated that the most reliable method to extract data analysis from a network is the “degree centrality”, which shows whether a node influences other nodes based on their number of connections. Furthermore, “weighted degree centrality”, a more modified version of degree centrality, considers the average mean of the sum of the weights of the links for all the nodes in the network (Opsahl *et al.*, 2010). With research areas as the nodes, the results will illustrate the research focus within the area and demonstrate the impact on other topics of interest. It was deemed fit to unravel the research focus of HRTs and how it relates to the resilience of the built environment. Research areas were ranked according to the level of activity and importance of key areas of study and the areas that have received less attention and remain unexplored and isolated (Hennig *et al.*, 2012; Golizadeh *et al.*, 2019). Table 1 illustrates the analysis generated using Gephi showing the ranking of the main research areas, weighted degree centrality signifying areas that have received the highest level of attention, compared with areas with lower weighted degree centrality values and their relative importance.

To illustrate the clusters, nodes in each cluster were distinguished using four different colours, as shown in Figure 5. Cluster 1 related automation in construction, Cluster 2 combined research on HRTs and collaborative robots. Cluster 3 indicates safety, whereas Cluster 4 identifies robotics designs. The identified clusters are similar to Aghimien *et al.* (2019), with similarities in identified clusters and the differences explained by the difference in queried keywords. The clusters are discussed below.

Cluster 1 – Automation in construction and autonomous systems. Automation in construction was identified as the central node in the largest cluster of the network and is the region mapped in pink with strong occurring keywords such as robot prefabrication,

Table 1.
Relative importance
of key research areas
on construction
robotics and human-
robot teams

Research area	Cluster	Degree centrality	Weighted degree centrality	Relative importance
Automation in construction	1	11	6.0	1
Human-robot teams	2	10	6.0	2
Safety	3	9	6.0	3
Robotics designs	4	5	5.0	4
Human-robot collaboration	2	4	5.0	5
Robot prefabrication system	1	5	5.0	6
Prefabrication	1	8	5.0	7
Robot perception	2	8	5.0	8
Human-robot interface	2	4	4.0	9
Sensors	4	4	4.0	10
Internet of Things	4	7	4.0	11
Human-machine interface	2	6	4.0	12
Disorders	3	3	4.0	13
Exoskeletons	3	5	4.0	14
BIM	4	4	4.0	15
Control	4	3	4.0	16
Autonomous	1	5	4.0	17
Human factors	2	4	4.0	18
Industrial robot	1	4	4.0	19
Robot systems	4	3	4.0	20
Machine design	4	2	3.0	21
Welding	4	3	3.0	22
Safety in robotics	2	6	3.0	23
Human-robot team trust	2	7	3.0	24
Computer vision	4	4	3.0	25
Robotic assembly	4	4	3.0	26
Information systems	4	5	3.0	27
Object identification	2	3	2.0	28
Three dimensional	1	7	2.0	29
Collaborative robots	2	5	2.0	30
Communication	2	7	2.0	31
Trust	2	7	2.0	32
Wearables	3	4	2.0	33
Earthwork	1	3	2.0	34
Vision based	3	3	2.0	35
Task performance	3	3	2.0	36
Unmanned aerial vehicles	3	2	2.0	37

autonomous systems, three dimensional (3D), earthworks and assembly. [Bock \(2015\)](#) identified construction automation as an emerging area with issues around it involving adoption [Aghimien et al. \(2019\)](#) and areas of application ([Bademosi and Issa, 2021](#)). In the design and assembly automation of the robotic reversible timber beam, [Kunic et al. \(2021\)](#) used HRC to develop an innovative workflow for automating the design and assembly of reversible timber structures. Some studies have examined how adoption challenges affect the implementation of robotics and HRTs. [Delgado et al. \(2019\)](#) used a mixed research method to investigate the factors limiting the adoption of robotics in the construction industry.

Similarly, using semi-structured interviews, [Pan et al. \(2020a, 2020b\)](#) identified the key factors that will influence the technological transformation of construction holistically by analysing the interactions between factors that will impact the future use of construction robots, whereas [Oke and Kineber \(2021\)](#) used a questionnaire survey to model the robotics

electroencephalographs assess their task-related cognitive load and alter robotic performance accordingly was designed by Liu *et al.* (2021b, 2021c). This was achieved by asking 14 subjects to complete a collaborative construction task with a robot under various cognitive pressure, which revealed that robots can achieve 81.9% accuracy in regulating their workplace. Such findings and studies are imperative in building trust amongst HRTs and facilitating safety designs. Because of low output in terms of publications and development in these areas, future research studies are required to advance safety in HRTs, social and workplace factors, ergonomics, HRC designs, human–robot interface, object identification and communication in collaborative interfaces.

Cluster 3 – Safety. Cluster 3 of the network centres emerged with sub-themes as: disorders, exoskeletons, wearables, vision based, task performance and unmanned aerial vehicles highlighting how these themes have emerged in underpinning the essence of robotics in the industry as important to improving health and safety of construction workers. The area is mapped in purple in the visualised networks shown in Figure 5. Capitani *et al.* (2021) designed an exoskeleton for construction workers that follows the specifications provided by an applicant in a model-based mechanical design of a passive lower-limb exoskeleton for assisting workers in shotcrete projection. The safety aspects in integrating robots with humans on site and what it portends for human factors were advanced by Boon *et al.* (2021) in safety enablers using emerging technologies in construction projects with Malaysia as a case study. Wang *et al.* (2021) adopted a case study approach to study interactive and immersive process-level digital twin for collaborative human–robot construction work. Other important factors such as trust, performance and physiological factors on human collaborators with robotics on sites have generated interest. Such studies include Gonsalves *et al.* (2021) assessment of a passive wearable robot for reducing low back disorders during rebar work by evaluating the exoskeleton related to task performance and physiological factors. However, the cost of the adoption of robotics and collaborative robots could hinder its use in achieving construction resilience. Previous studies have examined developing a general-purpose robot capable of performing a variety of tasks so that its use can be justified economically. Such studies are imperative to advancing its adoption by industry practitioners. The discussed keywords illustrate trending thematic areas with vast potentials to advance knowledge in the built environment.

Clusters 4 – Robotic designs. Cluster 4 of the network centres emerged with sub-themes as sensors, IoT, BIM, control, robot systems, machine design, welding, computer vision and information systems. These themes highlight the emerging areas and issues with robotics designs. These areas are of high importance for improving the versatility and use case of robotics in the industry. Xiang *et al.* (2021) examined augmenting virtual construction information directly in a physical environment using a camera-projector system to superimpose virtual 3D information onto planar or non-planar physical surfaces to further increase on-site productivity and safety. This came because of findings that because of the restricted field of view and non-negligible weight of goggles or helmets, they could cause more health, safety and efficiency concerns in complex real-world building projects.

Construction robotics and human–robot teams research areas towards resilience in the construction industry

Resilience describes how a system responds to unforeseen events, whether technical systems failures, human errors or external circumstances (Zieba *et al.*, 2009). For the built environment to be resilient, systems involved in its processes must incorporate resilience in its design and development. Autonomous systems must be resilient to deal with unanticipated circumstances. (Zieba *et al.*, 2009). Therefore, the design of these systems

must be bespoke to enable the systems to adapt to unplanned events. Recent designs in construction robotics and HRTs are geared towards ensuring the resilience of the systems in improving the industry's overall responsiveness, especially towards rapid urbanisation and shock events. They are discussed below.

Cluster 1 – Automation in construction and autonomous systems

Lundeen *et al.* (2017) studied methods for enabling autonomous sensing and modelling of construction objects, which will allow them to adapt to unexpected situations and perform quality work. Because of flexibility needed with human and robots' collaboration on site, this is imperative to prevent harm in uncharted regions requiring humans to collaborate with robots. In responding to infrastructure needs during shock events such as pandemics which tests the resilience of the AEC sector, enabling the capacity of collaborative robots in unexpected scenarios is important to achieve set objectives at zero safety risks. This has been studied by real-time simulation of construction workers using the combined human body and hand tracking for robotic construction worker system (Kurien *et al.*, 2018). Also, during shock events needing ability of the industry to be responsive to infrastructural needs, the use of robotic prefabrication system that uses a concept called "re-fabrication" to automatically disassemble a prefabricated structure and reassemble it according to a new design with little or no human intervention is useful in highly hazardous areas requiring zero human contacts (Kasperzyk *et al.*, 2017). This is further advanced in Abou *et al.* (2020) with a study on agent-based modelling to optimise the workflow of robotic steel and concrete 3D printers. Also, Wagner *et al.* (2020) used an experimental approach to study robotic fabrication through the conceptualisation, development and evaluation of TIM – a large, transportable and flexible robotic platform for building with timber. These studies are pointers to the direction future research is undertaking towards resilience in the construction sector.

Cluster 2 – Human-robot teams

With collaborative robots, image recognition is imperative in identifying objects and interpreting their characteristics and how to use them in construction tasks. Advancement in image recognition of robotics is imperative to their collaborative approach with human workers and thus able to enhance resilience in the industry because of the potentials of collaborative teams compared to traditional work teams. Zhou *et al.* (2021) used an experimental approach to develop an automated on-site object recognition approach for lifting tasks. Besides identifying and interacting with objects, the system is imperative for identifying human workers from objects. Similar to this is robot-assisted object detection for construction robotics by Ilyas *et al.* (2021). The robot system is equipped with perception sensors and intelligent algorithms and can help construction robotics identify construction materials, detect component installations and generate reports of their location and status.

Furthermore, in brainwave-driven HRC in construction, Liu *et al.* (2021a, 2021b, 2021c) developed a framework in which robots can capture workers' brainwaves using wearable electroencephalographs, assess their cognitive load concerning their tasks and adjust their performance accordingly. This approach is essential in robotics self-learning human experience to improve processes and workflow and enhance decision-making to achieve resilience effectively. To further improve contact-intensive tasks, Anna *et al.* (2021) use reinforcement learning to control robot movements which are imperative to avoid collisions with human collaborators and objects when deployed to the site or hazardous areas. This is also demonstrated in Liang *et al.* (2019), who used the human demonstration to teach robots to perform quasi-repetitive construction tasks. To assess the impact of force feedback in

robotics operations, [Zhu et al. \(2021\)](#) experimented with investigating the neurobehavioural performance of operators with a bilateral control system when they operate a typical industrial valve. Their impact on the nature of work and how this affects construction human collaborators is also important, as examined in [Ogunseju et al.'s \(2021\)](#) study on using a passive exoskeleton for hand-to-hand handling of materials. Further studies on exoskeletons to alleviate human strain in construction tasks, intelligent algorithms for robots to learn human skills and improve on it autonomously, accuracy in object identification and designs to advance safe deployment are integral to advancing resilience in the industry and to further subsequent designs and development.

Cluster 3 – Safety

Health and safety are also important in construction resilience, especially with an ageing workforce and reduced critical skills because of low entry arising from fear of hazards. An objective and systematic method for evaluating the value of semi-automated construction systems is proposed by [Ryu et al. \(2020\)](#) to assess the health and productivity impact of semi-automated work systems in construction. Also, [Kas and Johnson \(2020\)](#) guide leveraging hazard recognition tools and site-specific training when evaluating whether a unmanned aerial vehicles or robot will suit a particular application. [Wang and Zhu \(2021\)](#) presented a novel vision-based framework for capturing and interpreting workers' hand gestures as a human–robot interface in construction. The ability of the robot to understand and interact with human communication is vital to building trust in the systems critical to their deployment. While it also fosters safety and avoidance of risky tasks with humans, its advancement would justify and build reliance on usage in shock events to ensure the industry's resilience to rapid infrastructure demands. Pre-compensation algorithm cross-coupled to improve tracking performance in robotics is further essential in HRC to assist robots in navigating construction worksites with zero collisions with objects and humans ([Wang et al., 2016](#)). This is further important for safety given the unstructured nature of construction environments.

Clusters 4 – Robotic designs

In a collaborative welding system using BIM for robotic reprogramming and augmented spatial reality, [Tavares et al. \(2019\)](#) present a cooperative welding cell that combines human and robot operators for structural steel fabrication by leveraging BIM standards. [Tsuruta et al. \(2019\)](#) experimentally assessed the use of the mobile robot for marking free access floors at construction sites; this would enable workers to manoeuvre construction worksites better and improve HRC. The use of a BCI-based system for remote control of robots is investigated by [Liu et al. \(2021a, 2021b, 2021c\)](#) using a brain–computer interface. This is essential in the long-term strength of construction robotics in remotely monitoring and controlling production remotely with IoT-enabled devices, especially in events requiring zero human interaction, such as shock events. Other emerging trends in the use of robotics to improve the AEC sector's resilience and responsiveness, especially during shock events, is seen in a wheeled robot that drives posts and piles into the ground with a combination of vibrations and body mass with little human participation ([Melenbrink et al., 2020](#)). With the amount of time, safety risk and human workers require, this system's novelty improves the process while also eliminating the risk element.

Co-authorship network

A co-authorship network is imperative to identify researchers who are driving discourse on HRTs/robotics in construction, as represented in [Figure 6](#). A co-authorship network is a

powerful and useful analytical tool for assessing and identifying scientific collaboration trends, leading organisations, countries or individual scientists (Olawumi *et al.*, 2017; Saka and Chan, 2019a, 2019b; Babalola *et al.*, 2021). A co-authorship network was developed on authors who have contributed significantly to the human–robot thematic area in AEC. The minimum number of documents considered significant using VOSviewer was two documents with a minimum citation of three. Of the 218 authors, 29 met the threshold. The research impact was estimated based on publications, citation scores and link strength. The analysis shown in Figure 6 revealed the most productive authors as: Pan Wei, Kamar Vineet and Thomas Bock with five publications each. The limited clusters and collaboration depicted in the visualisation are not surprising as the field is slowly emerging. However, for stronger research output, scientific collaboration through shared expertise, funding and specialities is key to driving this emerging area (Golizadeh *et al.*, 2019). The analysis was created based on bibliographic data generated from Scopus and set the type of analysis set to “Co-authorship” as indicated in Su and Lee (2010) and Olawumi *et al.* (2017). The major clusters identified revolved around Pan Wei and Kamar, who also have the largest publication in the area. Extensive collaboration between researchers can reduce remoteness shown through the degree of disparity in the nodes. The blue colour depicts studies carried out in the past five years, whereas the green colour depicts studies carried out in the past two to three years; the yellow colour scheme indicates emerging studies (Liu *et al.*, 2021a, 2021b, 2021c).

Further analysis shows the clusters of collaborating authors; though disperse, it shows more weakness as clusters are limited to a few countries: the USA, Germany, Hong Kong, the UK, South Korea and China. The absence of Africa from studies in this field is a challenge to African researchers on the imperativeness of extensive collaboration with developed economies. There must be a deliberate commitment between African researchers and counterparts in developed economies to information exchange in keeping up with the times.

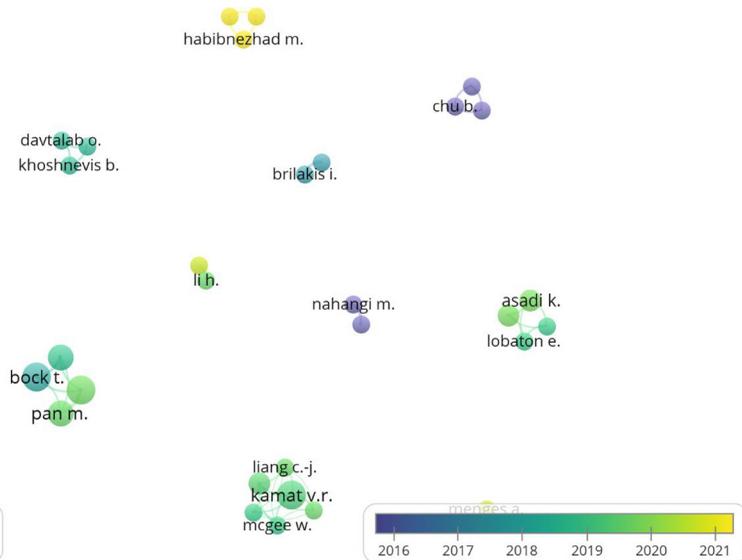


Figure 6.
Co-authorship
network

Publication per journals

Table 2 shows the publication sources identified from the Web of Science database, with the highlighted journals being the ten most cited publication sources with the number of documents published and the number of citations recorded. As stated in Olawumi *et al.* (2017); Saka and Chan (2019a, 2019b) and Babalola *et al.* (2021), citations refer to the number of times a scientific article or document is referenced in another article to reflect its scientific impact. The journal of automation in construction leads in both the number of documents published and the overall citation with 50 documents and 665 citations, respectively, outranking all other journals. Other journals have low publications between five and one in the thematic area. The sparse number of publications in journal sources indicates the low amount of research endeavour and efforts in the subject area as it is emerging. Through special issues focusing on thematic areas around HRTs, journals could drive studies in the field.

Author co-citation network

There were 5,255 authors cited in the data sets, a minimum number of citations set to 6, with 155 authors meeting the threshold as shown in Figure 4. The top-cited authors were Bock Thomas with 103 citations, Linner Thomas with 71 citations, Kohler Matthias with 54 and Kamat and V with 53 citations, as shown in Figure 7. The VOSviewer density visualisation indicates the influential networks. The author co-citation network visualises the influential documents in a data set (Olawumi *et al.*, 2017). The density visualisation is limited, showing the need for more extensive collaboration in this area.

Document co-citation network. The document co-citation network analyses the cited references within a data set (Saka and Chan, 2019a, 2019b). The density visualisation of the document co-citation network below indicates the top-cited documents in HRT/robotics research. A minimum number of two citations was set to visualise the network of 3,132 references. Bock’s (2015) study on the future of construction automation is the most cited, followed by Green *et al.* (2008) on HRC and Bock (2017), respectively. This is illustrated below in Figure 8.

Discussion

Conversation on resilience is vital to reinforcing the industry’s vulnerability to shock events. Rapid urbanisation, pandemics, natural disasters or changing stakeholders demands could profoundly affect the industry if it does not maximise the potentials robotics and HRTs offer in modernising and automating its processes. Bock (2015), the most cited publication in the

No.	Journal source	Documents	Citations
1	<i>Automation in Construction</i>	50	665
2	<i>Journal of Construction Engineering and Management</i>	7	2
3	<i>Journal of Building Engineering</i>	4	2
4	<i>Journal of Computing in Civil Engineering</i>	3	39
5	<i>International Journal of Automation and Computing</i>	2	3
6	<i>Architectural Science Review</i>	1	5
7	<i>Computer Applications in Engineering Education</i>	1	4
8	<i>Journal of Management in Engineering</i>	1	13
9	<i>Construction Innovation</i>	1	2
10	<i>International Journal of Engineering Education</i>	1	1

Table 2.
Publication sources

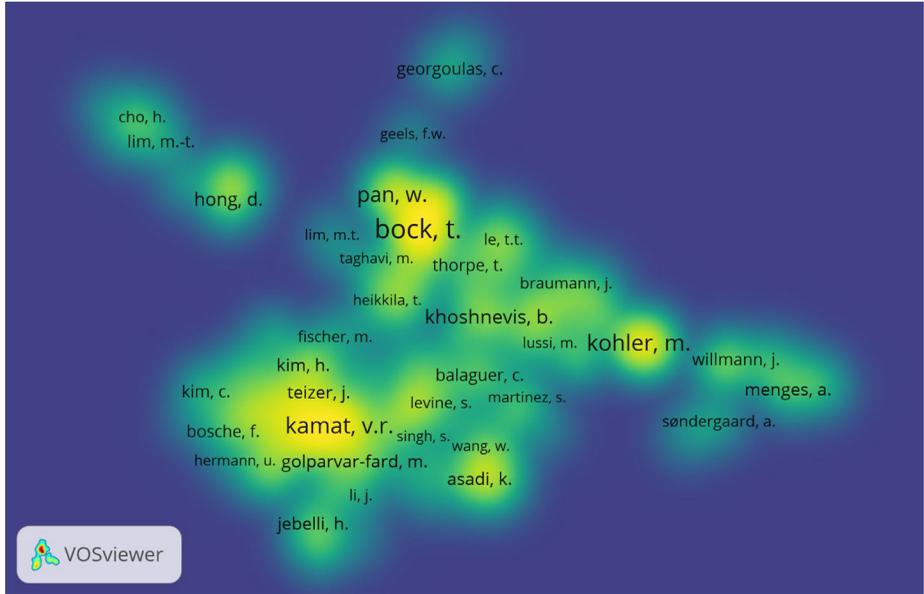


Figure 7.
Author co-citation
network

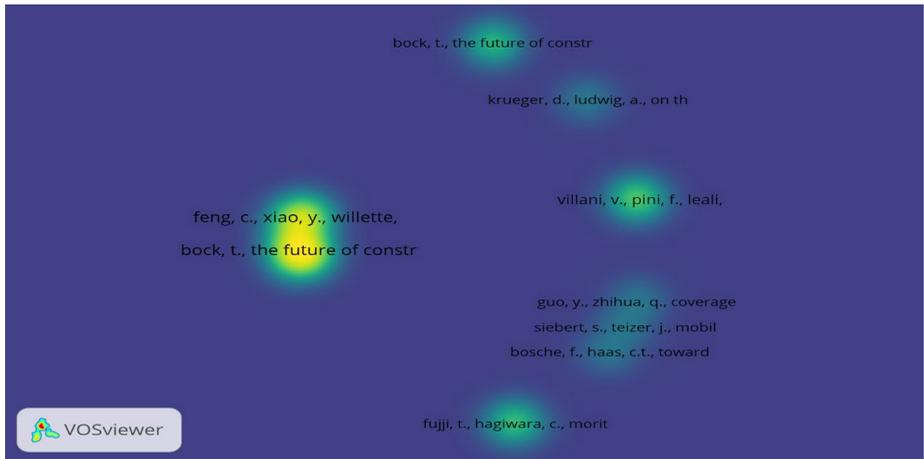


Figure 8.
Document co-citation
network

review, opined that the traditional approach, tools and processes in the delivery of infrastructure are lacking in efficiency and no longer sustainable, hence requiring methods that would improve the resilience of the built environment. The importance of HRC in construction resilience is demonstrated in that collaborative robots think beyond adapting robotics to people and promote mutual and sustained adaptation suited for different work tasks. The ability to bounce back quickly from adversity and respond to needs as signified in resilience in the construction sector would be determined greatly by optimised, automated and modernised operations, supply chains and infrastructure delivery processes. Central to

this is the use of robotics and HRTs (Bock, 2015). The need to achieve a resilient and responsive construction sector is at the heart of the increasing development and deployment of research in construction robotics. Shock events such as natural disasters, pandemics and hazardous accidents have troubled the construction sector, revealing its lack of resilience as evident in its need to shut down or inability to respond to rapid demands (Darlow *et al.*, 2022). In spite of the sector's complexity, some of its repetitive tasks, hazardous works and processes needing productivity can be undertaken by robotics which can continue operations unabated and remain largely unhindered by effects of shock events. The manufacturing industry, known strongly for its resilience, has achieved this primarily from the innovative use of emerging technologies, which is an aspect the construction sector lacks (Pan *et al.*, 2020). To promote resilient built environment, the study identified existing research clusters and future research areas as: Cluster 1 – Automation in construction: autonomous systems, earthworks, 3D modelling, assembly, fabrication and 3D printing/additive manufacturing (Bock, 2015; Kasperzyk *et al.*, 2017; Bogue, 2018; Aghimien *et al.*, 2019; Gharbia *et al.*, 2020). Cluster 2 as HRTs with sub-themes: Communication in collaborative teams, human–robot interface designs, perception and adoption factors, object identification, human and workplace factors and trust in robot teams (Wolf and Stock-Homburg, 2020; Reinhardt *et al.*, 2020; Liu *et al.*, 2021a, 2021b, 2021c; Gonsalves *et al.*, 2021). Exploring worksite factors is essential in ensuring that HRT collaboration is conducted in a conducive environment for the robot and the human worker. Because of the size of some robotics, these need careful studying alongside their design implications. In the worksite, critical issues emerging are on the influences of a limiting work area: dynamic terrain of the average construction site, manoeuvring around sites with robotics, the complexity of projects and the task sequence between robots and human workers who are used to teaming only with humans (Sellner *et al.*, 2006; Xiang *et al.*, 2019; Dobra and Dhir, 2020). The implementation of robots to execute these risky jobs in a collaborative team under the control of humans can prove highly beneficial to the safe delivery of construction projects (Aghimien *et al.*, 2019). The uniqueness of individual projects, varying construction site processes and inaccuracies in components of buildings are also vital areas that require utmost attention. Cluster 3 integrated safety in robotics: exoskeleton to alleviate disorders and strain, task performance and vision-based development to improve collaborative human safety (Bademosi and Issa, 2021). Cluster 4 identifies issues around robots design with themes on industrial robots, machine design, welding, intelligence in robotics, use of sensors to improve feedback, computer vision to enhance object identification, robotic assembly, information systems, IoT and integration with BIM (Reinhardt *et al.*, 2020; Xiang *et al.*, 2021).

For robotics design factors, the rigid movements of robots are imperative to avoiding collision with humans and collision with objects on sites (Bryan and Mahya, 2021). Other areas of research concerned with the design of robots for HRTs seek to explore reducing the cost of procuring robotics, maintenance cost, social skills of robots, intelligence of robots, size, adaptation to gestures, integrations with HRTs and degree of collaboration.

Research in HRTs is further evolving to critically focus on human factors and the social consequences such adoption could portend for the livelihood of workers. Human factors also examine social issues such as trust issues in the safety of the robot, trust in the effectiveness and efficiency of the robot on site and trust in the ability of the robot to collaborate in an HRT.

Research thematic focus vital in construction robotics and HRTs in contributing to the resilience of the built environment includes: fault tolerance, the ability of the robot to maintain itself and continue its functions in spite of internal and external challenges over a

period of time with justifiable trust (Zhang *et al.*, 2017). Privacy and monitoring with robots on site and the effects this hold on the human psyche, the fear of losing Jobs, psychological factors, acceptance of robots leading teams and technology acceptance are also critical in this area. Increasing publications also focus on sustainability, BIM integration with robotics (Davtalab *et al.*, 2018), unmanned aerial vehicles (Martinez *et al.*, 2020), speed of robotics and implications on safety (Salmi *et al.*, 2018) and impact management and risk of compression in robotics adoption. Critical areas that are also needed to explore are governance aspects of HRTs looking at policies around the adoption of HRTs to protect workers and safety standards and regulations to ensure zero accidents occur in projects adopting collaborative robots (Delgado *et al.*, 2019; Dobra and Dhir, 2020; Liu *et al.*, 2021a, 2021b, 2021c).

To ensure resilience and responsiveness, it is important to upskill construction workers in line with emerging future competencies. Therefore, the adoption of robotics allows upskilling and redeploying construction workers to more value-adding positions. For HRTs, this is more important to build trust and ensure safety in collaborating with robots on site. This is evident in Adami *et al.* (2021), who examined the effectiveness of virtual reality (VR)-based training on improving construction workers' knowledge, skills and safety behaviour in robotic teleoperation. Using experimental methods, the study compared VR-based training and traditional in-person training on construction workers' knowledge acquisition, operational skills and safety behaviour during robotic teleoperation. While there are low outputs in terms of education pathways for human integration with robotics on construction sites, simulation-based training is imperative. Wen and Gheisari (2020) iterated this by emphasising that VR and A.R. can facilitate workers training in adopting these emerging technologies. Therefore further studies in adaptability in sustaining resilience must take into cognisance how interconnected systems integrating technologies, systems and humans within the industry can draw on shared strengths of each aspect to accommodate shock events.

Research in robotics and HRTs has been vastly explored in the manufacturing sector with little output in the architectural, engineering and construction sectors. The visualisation and analysis reveal the emerging area and is critical to research in robotics (Aghimien *et al.*, 2019). There are more publications from the USA than other countries with no visibility from Africa. The relatively few studies in the area indicate low awareness and direction towards this aspect of research, further compounded by funding and digital requirements to drive this level of research. Bademosi and Issa (2021) stated that low technological advancement and inadequate research and development have been described as enabling the slow growth of the AEC industry. The visualised author network validated that research on HRTs is in infancy. Sparse clusters indicate a lack of collaboration between researchers in this emerging field (Kamath and Sharma, 2019). The review also revealed no clear government policies or mandates across the globe regarding HRTs. The high cost of procuring robots, acquiring their technical know-how and maintaining the hardware are critical factors that could slow down efforts in this area of research (Ajoudani *et al.*, 2017). The inadequacy of empirical studies on the use-benefit of HRTs compared to the current traditional construction method would also signify industrial practices would be reluctant in investing in the novel innovation as this would need to be balanced with the current adoption of other digital technologies in the industry such as BIM and reality capture. Because the construction industry is aggregated between large firms and small and medium-sized enterprises (SMEs), future studies and research in design would need to examine reducing the cost of procurement and maintenance for proliferation with SMEs as SMEs are characterised by limited resources for investing in digital technologies.

Conclusion

HRT/robotics is an emerging field in the architecture, engineering and construction sector with immense potential for improving construction productivity. Research in the area is at an early stage but is gradually improving. The study identified the research trends in HRTs/robotics in the construction industry and identified emerging and lacking aspects. The study used a quantitative approach using the scientometric approach to answer predefined objectives. It is, however, instructive for more studies to be carried out in HRTs to critically evaluate the perception of humans to share the workplace with robots and consequent implications on workplace issues. While there would be sparse studies in an emerging research area, there is the need to advocate for more inclusive and extensive research collaboration between institutions. HRTs/robotics, therefore, present an opportunity to increase economic delivery through enhanced infrastructure delivery and not to be seen as a threat. While there are concerns about changes in the workforce, HRTs offer the need to improve skills and expertise – a largely inevitable reality for the future of work in achieving construction resilience. In spite of the contributions of this research, the results only reflect data sets generated within the Scopus database in ten years. Further studies would be imperative in narrowing the focus to HRTs and considering other databases while using other literature review approaches to further enrich research in this area.

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