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Review

Construction Robotics and Human–Robot Teams Research Methods

Adetayo Olugbenga Onososen [1,*], Innocent Musonda [1] and Molusiwa Ramabodu [2]

1 Center of Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2028, South Africa
2 Department of Construction Management and Quantity Surveying, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2028, South Africa
* Correspondence: onososen@outlook.com

Abstract: Though studies in construction robotics and human–robot teams research have explored varying themes, an in-depth study of the state-of-the-art of methodological paradigms appropriate for construction robotics research is hitherto lacking, taking into consideration that several studies have highlighted conflicting methodological components such as research design, methods, data sources, data types and analytical techniques. To better understand this underexplored area, this study uses a four-stage review approach utilising a scientometric and systematic analysis method based on 112 articles. Using statistical analysis to evaluate the relationship between research components, the study reveals strong associations between components of research methods, data sources and analytical techniques. Researchers are also increasingly looking to mixed paradigms in data sources and designs, highlighting a methodological plurality in construction robotics research. Implications on what this means for the future of construction robotics, policy and stakeholders are discussed in the study.

Keywords: collaborative robots; construction robotics; human–robot teams; human-technology interaction; research methods; scientometric; systematic review; cobots; mixed review

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1. Introduction

The underperformance of the high volume of research output in the built environment in regard to contributing to improving industry practices is underpinned by the inability to provide richer insights from studies not adopting best-fit research methods to address built industry problems [1]. Previous studies have attributed this to long-standing controversial methodological debates, the prominence of the rationalistic paradigm, a lack of interest in studying methodologies and inadequate academically taught programs on research methods in the architectural, engineering and construction sectors [2–4]. This, however, is not sustainable, given the introduction and growing adoption of digital technologies in the built environment necessitating richer research insights to assist organisations and stakeholders in adapting and dealing with the changing nature of the construction sector.

Given the benefits of technologies such as construction robotics and human–robot teams in improving productivity, safety and resilient construction delivery, focusing on appropriate methodologies to improve research output and achieve more human-friendly and safe robotics design and development is imperative to their adoption. However, little is known about the research methods adopted in extant construction robotics studies.

Previous studies such as [1,5] support these assertions and further indicate a gross lack of theoretical contributions from research studies. In a review of research methodologies in offsite manufacturing, [1] revealed that 85.1% of studies make no theoretical contribution. Such studies lacking theoretical and conceptual placing are unsatisfactory as they lack a structured and articulated perspective through which empirical problems can be observed or analysed [6]. The issue has grown in importance in light of the recent inability of studies to adequately explain particular phenomena and thereby bridge what is indefinite and what is concrete. The interlinkage between research designs in establishing adequate theoretical and conceptual approaches for experimental phenomena indicates the need to understand the research methods adopted in construction robotics extant studies. The need to drive productivity, improve safety and enhance work in industrialised construction settings has spurred rapidly growing research interests in the design and development of construction robotics [7–9]. This has also generated growing studies on the collaboration between construction workers and robots [10–12].

However, studies have not focused on a comprehensive review of the thematic construction robotics research methods. It was argued by [1] that studies that have attempted to review methods only approach this question on a superficial basis as part of other objectives and often lack a comprehensive and in-depth overview. In addition, given the various sub-thematic areas underdeveloped in construction robotics research, little methodological discussions do not help improve pathways to conducting adequate studies on the existing phenomena in robotics design and development in the architecture, engineering and construction (AEC) sector. Furthermore, as an emerging thematic area, clearing the uncertainty on the rigour in construction robotics research methods is critical to assisting researchers in unravelling the difficulties associated with understanding methodological discussions in the construction robotics and human–robot teams literature. As the lack of attention to design can result in eliciting data unfit to answer research questions, understanding this is critical to set apart an average study from one that addresses a problem.

To this end, this study aims to unravel the state of the art in the construction robotics and human–robot teams research methods. Specifically, the study answers questions on the research methods adopted in extant construction robotics studies and maps out the established relationships between different components of the research methods used in construction robotics. This undertaking aids in understanding what research methods have evolved and how they have shaped emerging research themes. This offers perspectives from the lenses of innovative approaches and new thinking in research methods for construction robotics. In addition, it helps researchers justify and support the intended research paradigms for their studies as well as informs emerging researchers on the possibilities currently available in methodological approaches. This paper is divided into five sections. Section 1 introduces the study and research objectives. Section 2 highlights components of the research process from conceptualisation to research methods. Section 3 presents the research findings and Section 4 presents the discussion of the results while Section 5 offers implications, limitations, and our conclusion.

Components of the Research Process, from Conceptualisation to Research Methods

As stated by [1], research methods have well-established links to which most scientific research complies in order to meet the precision required of scientific knowledge production. These methods are based on well-established and grounded research philosophies. As identified by [13], the main worldviews guiding these approaches are: post-positivist, constructivist, transformative and pragmatic. The deterministic philosophy of post-positivism maintains that causes determine effects or outcomes, while a constructivist views individuals as developing subjective meanings based on their experiences with objects or things [14]. The authors further described a transformative worldview as concentrating on the needs of groups and individuals that may be marginalised. Meanwhile, pragmatism uses all available approaches to understand the problem rather than focusing on methods. While worldview is important in guiding the researcher to properly conceptualise the nature of problems and methods, [3,15] state that non-alignment to these worldviews and their correspondent understandings of the established relationships between components of research methodology raises doubts on the validity of such research endeavours. This is further highlighted by [1] stating that the research method chosen greatly determines the type of research design, which subsequently influences decisions on the types and sources of data drawn and the appropriate analytical techniques to ensure the data give the right results.

Extant studies considering qualitative methods are mainly linked to the interpretivist perspective of philosophy; quantitative approaches, on the other hand, tend to relate to positivism. Meanwhile, an argument can be made for the mixed approach, where the combination of both qualitative and quantitative approaches provides a more complete understanding of the research problem than either approach alone. The danger to this, as seen in several studies, is to adopt a mixed approach to move along with the times; while this does not show adequate understanding of the need for mixed approaches, it is essential to reiterate that academics must ensure the methods work together in such a way that they provide additionality and address the research questions [13,14,16]. Having presented the components of the research process, the reviewed research methodologies are presented based on the following objectives:

1. How has construction robotics research evolved, and what are the key thematic areas?
2. What types of research methods are employed in the construction robotics and human–robot teams literature?
3. What is the use of theories and conceptual frameworks in the construction robotics literature like?
4. What research designs, data sources and analytical techniques are employed in the construction robotics and human–robot teams literature?
5. What is the nature of the relationships between key components of the research methods in the construction robotics and human–robot teams literature?

2. Research Method

This study adopted a four-stage method to answer the research objectives based on the research questions. The first stage involved the search for publications, the exclusion criteria were applied in the second stage, and the third stage involved a demonstration of scientometric analysis. Lastly, critical analysis was carried out through a systematic literature review. The four-stage literature review approach maximised the strength of both a scientometric and systematic method to avail a comprehensive study of the research objectives. This approach has been well-supported and adopted in built environment studies [17,18]. The process is shown diagrammatically in Figure 1.

2.1. Stage One: Search for Publication

As illustrated by [18], systematic literature review guidelines describe at least three types of inclusion criteria: academic databases, keywords to query and publication type to include. The Scopus database has a wide coverage and is the preferred academic database for reviews, given the quality of articles within its reach [19–21]. Consequently, publications were retrieved from the Scopus search engine/academic database with the query "Robotics" AND "Construction" with no year limitation; the output was 1071 publications. The search was conducted in March 2022.

2.2. Stage Two: Exclusion Criteria

The use of exclusion criteria in systematic and scientometric reviews is a standard protocol relied upon to aid the likelihood of producing reliable and reproducible results and reduce the capture of irrelevant studies; this approach has been well adopted in previous studies [22,23]. The exclusion criteria were adopted in three stages: The documents were limited to papers published in English and related to construction management. Articles not published as journal research output were removed to only include inputs that contained the credible, valid and scientifically rigorous work needed to understand the research objectives appropriately. Non-journal publication removal and abstract proofing were carried out to ensure relevance to the research questions. This yielded a total of 112 publications. This process was similarly adopted in [24–26].

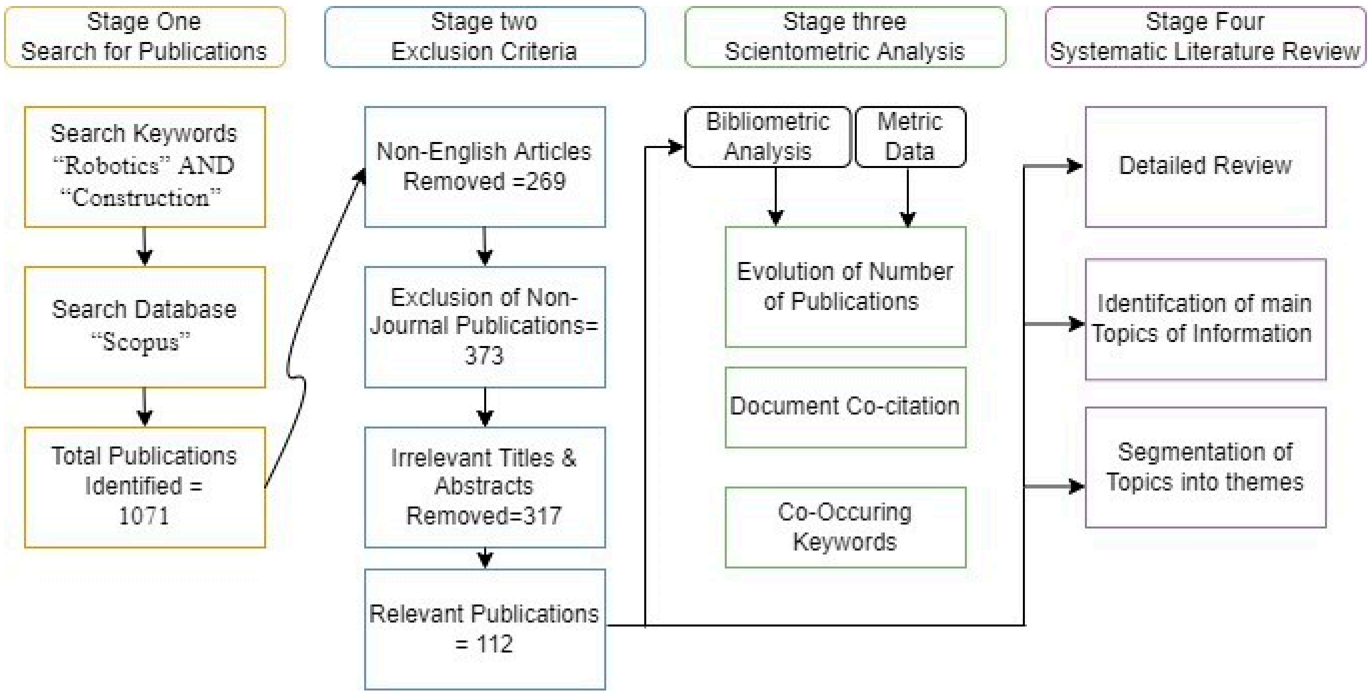

Figure 1. Research method for the study.

2.3. Stage Three: A Scientometric Analysis

In the scientometric analysis, metric data were extracted from the reviewed articles to generate the evolution of the number of publications in construction robotics over the years. This was imperative to understanding the trends and interest in construction robotics over time. Furthermore, bibliometric analysis was carried out to generate document co-citation and co-occurring keywords. The co-occurring keywords network was the linkage of co-occurring keywords in the documents, which reflected the themes of the research publications. This revealed the relationship between the emergent research themes and methods adopted over the years. The document co-citation network was the network of cited references in the analysed documents, revealing similar trends in the research themes and related works often cited in extant studies. This was essential to identifying authors who received significant peer recognition and understood how the quality of their works was improved by the research methods adopted [27,28].

2.4. Stage Four: Systematic Literature Review

During this stage, the main information topics were identified and grouped into key information categories. The categories were discussed under:

i. The identified research themes and methods;
ii. The types of research methods;
iii. The use of theories and conceptual frameworks in the construction robotics literature;
iv. The research designs employed in the construction robotics and human–robot teams literature;
v. The data sources used in the construction robotics and human–robot teams literature;
vi. The analytical techniques used in the construction robotics and human–robot teams literature;
vii. Analysing the relationships between key components of the methodologies in the construction robotics and human–robot teams literature.

3. Results

3.1. Overview of Publications and Methods

The overview of publications and methods was carried out to reveal the existing trends and evolution of knowledge regarding the research methods adopted in construction robotics research.

The overview of publications and methods was evaluated between 1987 and 2021. The evolution of publications per year and the frequencies of the respective research methods adopted are shown in Figure 2. The figure shows an upward trend in research associated with construction robotics. Starting in 2017, the linear evolution of publications was identified, while the years between 1987 and 2016 had a non-linear evolution. The high rate of publications between 2020 and 2021 shows that the topic attracted highly significant discussion and was important to the scientific community. The 112 articles were retrieved from 40 journals, with 45% of the articles published in Automation in Construction, 4.5% published in the Journal of Construction Engineering and Management, 4% in the Journal of Building Engineering, 6% in IEEE, 3% each in the Journal of Architectural Engineering, Journal of Information Technology in Construction and Journal of Management in Engineering and 2% each in the Journals of Autonomous Robot, Sustainability, Engineering, Construction and Architectural Management and the International Journal of Architectural Computing. Other journals were the source of 1% of the total contributions. The peak of publication and the concentration of articles in Automation in Construction is consistent with similar studies [1,29].

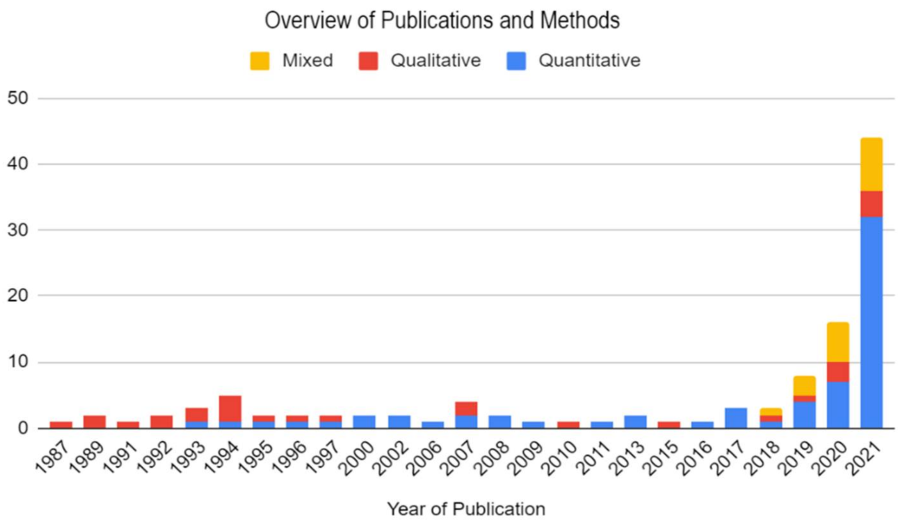

Figure 2. Overview of Publications and Methods.

3.2. Most-Cited Publications

The number of citations was also analysed and is presented in Figure 3 below. Amongst all the publications, the most-cited publication was [30]. In "the future of construction automation: Technological disruption and the upcoming ubiquity of robotics", [30] used a systematic review approach in discussing construction automation and robotics. The article is critically important to construction robotics as it details a general overview of robotics and further highlights the value of robotics drive-in construction project delivery. Other well-cited documents, however, used the case study and experimental approach, including studies such as [31], "task planner design for an automated excavation system", and [32], "High-performance non-linear motion/force controller design for redundant hydraulic construction crane automation." Further documents included [33–35], which all used case studies as the research method. Similar studies that adopted a systematic review and were well-cited were [36], "Trend analysis of research and development on automation and robotics technology in the construction industry", and [37], "Drilling systems automation—Preparing for the big jump forward". These findings are in order with the findings of [38].

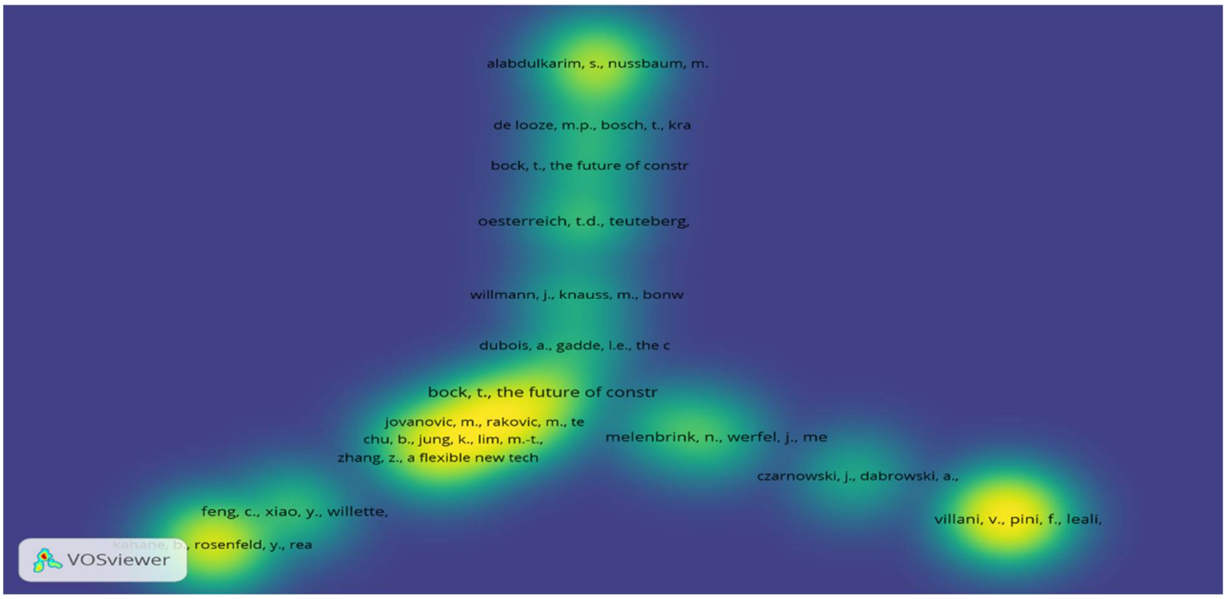

Figure 3. Most-cited publications.

3.3. Co-Occurring Keywords

The created network, shown in Figure 4, visually represents the number of occurrences of a keyword by the node size and the degree of co-occurrence between keywords by the link thickness. As expected, "robotics" is the biggest node of the created network. Other keyword co-occurrence networks with strong links were summarised into thematic areas, and the key questions in these areas are presented in Appendix A.

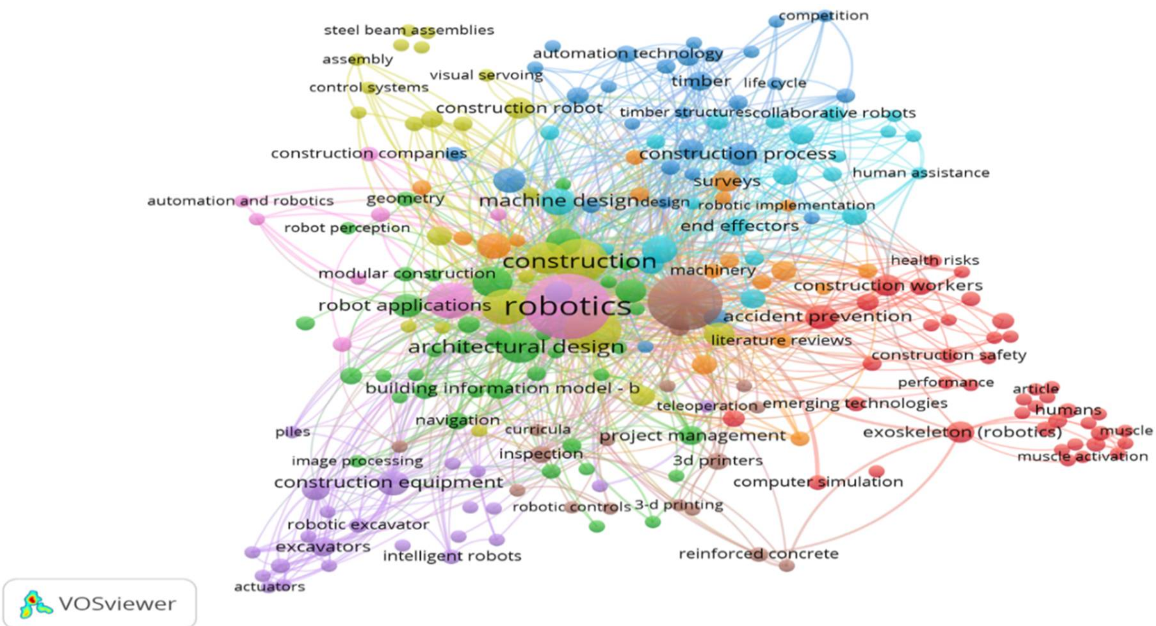

Figure 4. Co-occurring keywords.

3.4. Contextualising the Methodologies Used in the Reviewed Articles

Contextualising the research methods in the reviewed articles helps us understand how the research objectives influence research methods. In their study, [1] highlighted that in categorising the research themes based on reviewed articles, the thematic area of each article could be matched against the research method. The emergent thematic areas were mapped from the co-occurring keywords, as often utilised in bibliometric analysis, and summarised into categorical areas in line with the research directions of extant studies [39,40]. The 112 articles were reviewed for aims/objectives, research question and contributions of articles sampled, after which we extracted the relevant thematic areas as summarised in Appendix A. In scientific research, themes do not often predict applicable research methods but instead depend on objectives within thematic areas; some methods occur more frequently than others. This knowledge is critical to understanding the nature of the problem within these fields and the adopted methods that fit the studies. As seen in Figure 5, the result supports the existing arguments that positivistic ontologies and quantitative methods dominate research in construction robotics. In the thematic areas of automating construction plants, equipment and systems, 12% of the studies fell under quantitative methods [41,42]. Quantitative methods also accounted for 17% of robotics design and development [34,43,44], 6% in ergonomics, health and safety [45–47] and 4% in collision avoidance/site navigation in human–robot teams [48–50]. Compared to popular perspectives, qualitative methods were revealed to be prominent amongst research themes in construction robotics, followed by considerable usage of mixed approaches. This supports the earlier assertion that research objectives are the indicators of the research design to be adopted.

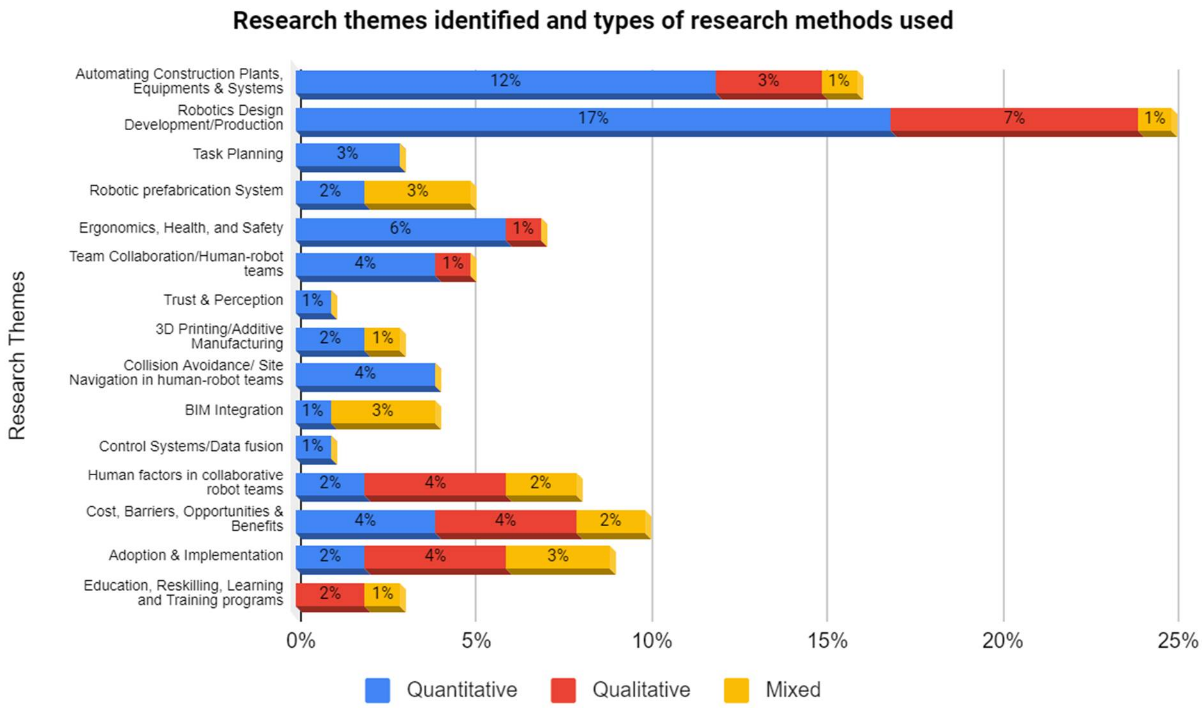

Figure 5. Research themes identified and types of research methods adopted.

3.5. Types of Research Methods Used

In offsite manufacturing research, [1] revealed that positivistic ontologies and quantitative methods were the preferred research design and were commonly used. In mapping out the research focus of construction robotics research, [38] revealed that the quantitative approach was the most adopted, with major studies using the experimental and case study approach. This is consistent with the findings of this study, which indicate, as shown in Figure 6, that the quantitative research method was the most used, comprising 67% of the sample, followed by the qualitative approach with 27% and mixed-method with 18%. While [5] claimed that qualitative methods are more popular in construction management research, this does not apply to the field of construction robotics, as shown in this study.

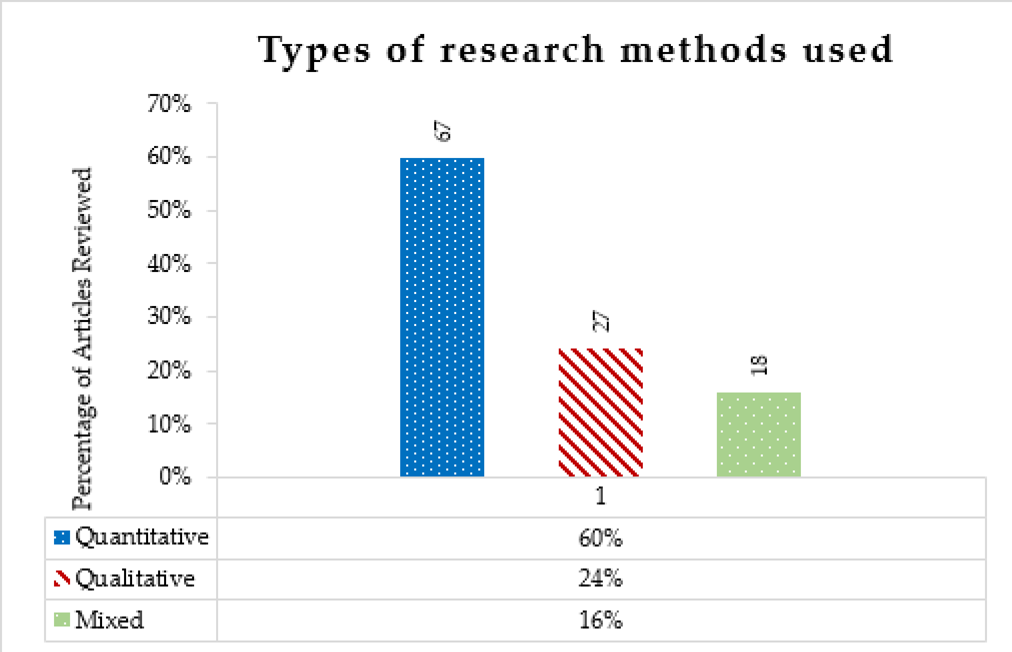

Figure 6. Types of research methods used.

3.6. Use of Theories and Conceptual Frameworks in the Construction Robotics Literature

Is there any need for theory in research? It was posited and argued by [6] that theories, as a body of concepts and principles, significantly improve the understanding and explaining of a particular phenomenon and create a structured set of lenses through which research objectives can be achieved. This demonstrates the need for theoretical and conceptual frameworks in construction robotics research. This argument was further affirmed by [16], who claimed that theory offers "methodological advice and guidance" and hence remains "essential for adopting appropriate methods of data collection, resultant data sets and analyses". Long before this, there was no empirical evidence indicating the frequency of the use of theory in construction robotics and human–robot teams. However, our study reveals that of the 112 articles reviewed, only 7% used a theory/theoretical framework while 21% used a conceptual framework/model. This is shown in Table 1.

Table 1. Use of theories and conceptual frameworks in the construction robotics literature.

Theory and Conceptual Frameworks	Frequency	Percentage
Used a theory/theoretical framework		
Yes	8	7%
No	104	93%
Total	112	100%
Used a conceptual framework/model		
Yes	24	21%
No	88	79%
Total	112	100%

3.7. Research Designs Employed in the Construction Robotics and Human–Robot Teams Literature

Figure 7 shows the research designs adopted in the reviewed articles. The experimental design was the most frequently adopted at 54%, followed by systematic reviews at 19%. The results also show that hybrid research designs such as experiments and case studies were adopted in 10% of the articles, while other standalone designs such as experimental modelling, case studies and surveys were adopted in 7%, 5% and 3% of the articles, respectively. Other research designs identified were survey and interviews (2%), bibliometric review (2%), interviews (2%), systematic review and survey (1%), focus group and survey (1%), literature and case study (1%), literature review and survey (1%), Delphi survey (1%), experiment and observation (1%) and process analysis (1%). It is not surprising that experimental research design was the most adopted given the nature of research in construction robotics [51]. The high adoption of review approaches is also consistent with findings from extant literature, as seen in [38], which found that review studies were well-cited in construction robotics research, with the review study [30] as the most cited. This is also an established trend in the scientific field as systematic review papers often receive more citations than original articles. However, with the increasing number of reviews, attention to quality is essential to ensuring they offer insightful contributions [52,53]. Case studies in standalone and hybrid designs also made up a large proportion of the designs adopted, a finding consistent with [54], which noted case studies as highly common. Given the need to showcase the potential of construction robotics on-site and in collaborative work with humans, case studies are imperative to achieving the proof of concept. Modelling was also well-adopted and was identified by [1] as an increasingly adopted approach for research studies.

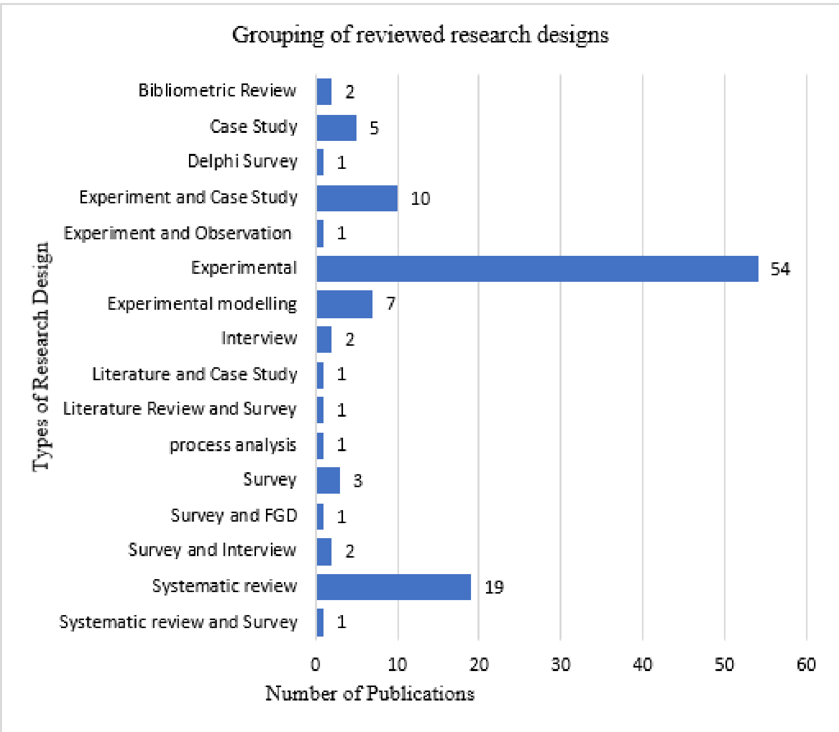

Figure 7. Research designs employed in the construction robotics and human–robot teams literature.

3.8. Data Sources Used in Construction Robotics and Human–Robot Teams Literature

We elicited 13 data sources from the 112 reviewed articles on construction robotics research. These data sources utilised standalone data sources and a combination of data sources as hybrid data sources. Figure 8 shows eight stand-alone data sources and five hybrid data sources. Amongst the stand-alone data sources, sources from experiments were the most adopted, followed by academic literature, surveys and expert interviews. Meanwhile, in the hybrid data sources, literature and expert interviews were the most commonly adopted, followed by project information and literature, experiment and observation, literature, expert interview and focus group discussions and literature and brainstorming.

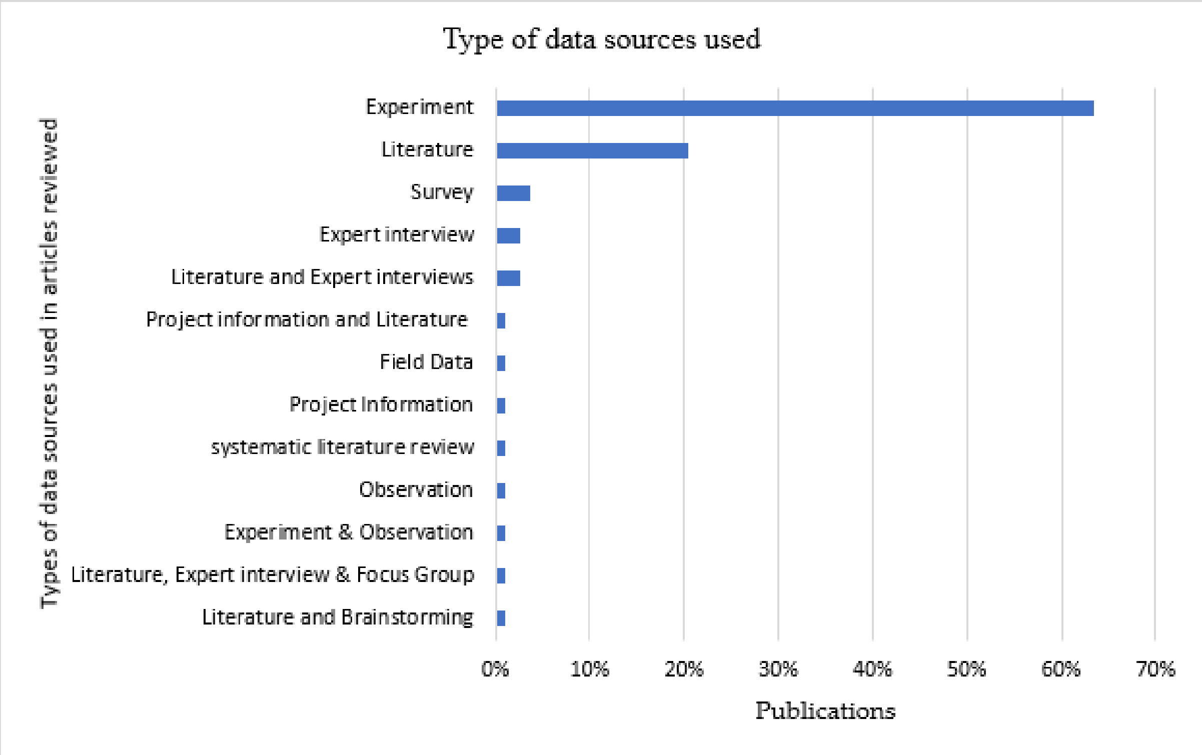

Figure 8. Data sources used in the construction robotics and human–robot teams literature.

3.9. Analytical Techniques Used in Construction Robotics and Human–Robot Teams Literature

The appropriateness of the analytical techniques used to evaluate research objectives and provide the right insights is imperative to advancing knowledge. They aid in examining the complex relationships between variables and guide the understanding and interpretation of the nature of the problem in research. In understanding the nature of analytical techniques in construction robotics research, we found 28 approaches to analysing data, with 18 making up stand-alone analytical techniques and 10 being hybrid analytical techniques, as shown in Figure 9. Of the two categories, modelling comprised 58% of the total review. However, while content and discourse analysis was the second-most-used analytical approach, this is not surprising given the increasing number of literature review publications in construction robotics as noted by [38] and the use of the literature to support most studies and place them within existing research paradigms. Simulation, descriptive and statistical analysis, scientometric analysis, and statistical analysis were also adopted frequently. The results show that despite the prevalence of quantitative analytical techniques, qualitative analysis is also gaining ground in construction robotics research. The results are consistent with [1,54], who found that modelling, content analysis, statistical analysis, and descriptive statistics were the most adopted analytical techniques.

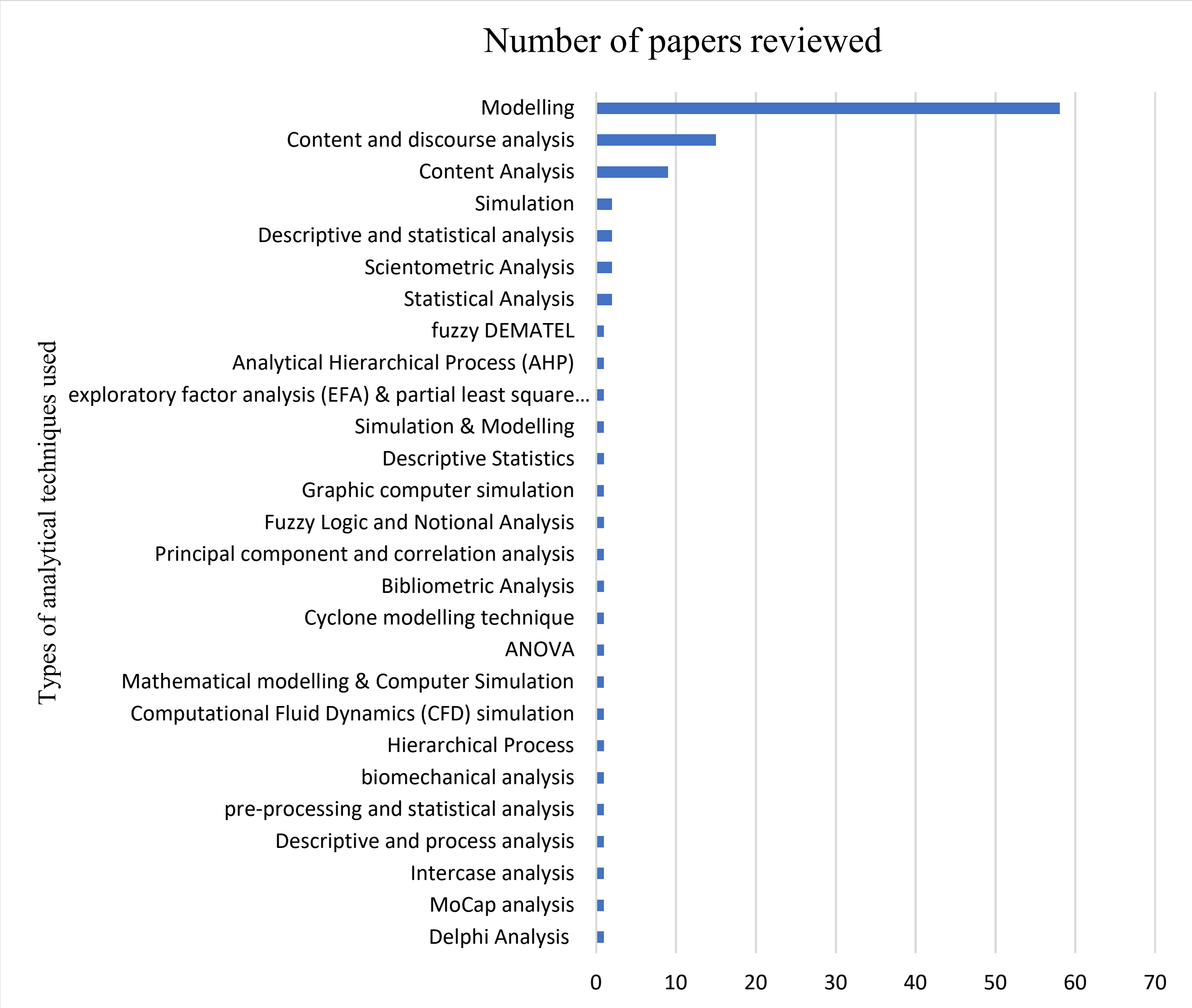

Figure 9. Analytical techniques used in the construction robotics and human–robot teams literature.

3.10. Analysing the Relationships between Key Components of Methodologies in the Construction Robotics and Human–Robot Teams Literature

To analyse the relationship between key components of research methods in the construction robotics literature, a null hypothesis (H0) following [1] was adopted. The null hypothesis postulated in the study was that there existed an equal distribution between any paired components of the research methodology. Thus, any test of association should result in no statistically significant association. Furthermore, [1] mentioned that for the components of research methods initiated in construction robotics research to match the relationships between the previously outlined components, there must be a statistically significant correlation between the pairs of components. Not achieving this would indicate incoherence in the research methods outlined in the reviewed construction robotics articles.

3.11. Relationship between Research Methods and Research Designs Employed in the Construction Robotics and Human–Robot Teams Literature

To evaluate the relationship between research methods and research design employed in the reviewed articles, cross-tabulation of the variables, as shown in Table 2, was utilised to interpret the relationship. The findings reveal that most studies adopted the experimental research design (78%) as a quantitative approach. Also, some studies adopted the experimental research design in a mixed-method research approach. This is validated by the experiment and case study research design being 56% mixed-method, showing that most authors triangulated the experiments on construction robotics by testing real-life scenarios in case studies. The proportion of research method to research design shown in the cross-tabulation also reveals an uneven relationship. For instance, systematic reviews employed qualitative methods 73% of the time and mixed-method designs 0% of the time. This trend prevailed across the table.

Table 2. Crosstabulation between research methods and research design employed in the construction robotics literature.

Research Design	Research Methods: Quantitative Methods	Qualitative Methods	Mixed Methods	Grand Total
Bibliometric review	2 (3%)	0 (0%)	0 (0%)	2 (2%)
Case study	2 (3%)	3 (12%)	0 (0%)	5 (4%)
Delphi survey	0 (0%)	1 (4%)	0 (0%)	1 (1%)
Experiment and case study	0 (0%)	0 (0%)	10 (56%)	10 (9%)
Experiment and observation	0 (0%)	0 (0%)	1 (6%)	1 (1%)
Experimental	53 (78%)	0 (0%)	1 (6%)	54 (48%)
Experimental modelling	7 (10%)	0 (0%)	0 (0%)	7 (6%)
Focus group and survey	0 (0%)	0 (0%)	2 (12%)	2 (2%)
Interview	0 (0%)	2 (8%)	0 (0%)	2 (2%)
Literature and case study	0 (0%)	0 (0%)	1 (6%)	1 (1%)
Literature review and survey	0 (0%)	0 (0%)	1 (6%)	1 (1%)
Process analysis	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Survey	3 (4%)	0 (0%)	0 (0%)	3 (3%)
Survey and interview	0 (0%)	0 (0%)	2 (11%)	2 (2%)
Systematic review	0 (0%)	19 (73%)	0 (0%)	19 (17%)
Systematic review and Survey	0 (0%)	1 (4%)	0 (0%)	1 (1%)
Grand Total	**68 (100%)**	**26 (100%)**	**18 (100%)**	**112 (100%)**

Pearson Chi-square (χ^2) = 209.13, df = 32, $p < 0.001$, Cramer's v = 0.96.

As stated by [1], this unevenness strongly indicates that some research methods were used more frequently for some research designs than others. We used the chi-square test as a statistical analytical technique to compare the observed results with the expected results to test if there was a significant difference. The Pearson chi-square test of independence between research methods and research design revealed a statistically significant association between the two components (χ^2) (32, n = 112) = 209.13, $p < 0.001$. To measure the substantive significance in showing how strong the relationship was, Cramer's v = 0.96 signified a strong association, where 1 is a perfect relationship and 0 is no relationship. Therefore, this finding rejects the null hypothesis of equal distribution of research methods across the research designs in the construction robotics literature. These results support the idea per [1] that the association between research methods and research design is coherent with the proven relationship within the component research methods.

3.12. Relationship between Research Methods and Analytical Techniques Employed in the Construction Robotics and Human–Robot Teams Literature

The crosstabulation between the Research Methods and Analytical Techniques used in the construction robotics literature, as presented in Table 3, reveals an uneven distribution. It is interesting to note that 48% of quantitative studies employed modelling with no qualitative method adopting the approach in the analytical techniques. One unanticipated finding was that contrary to [1,55,56], which found similar results but no mixed method using modelling, articles in robotics saw 56% of mixed-method approaches adopt modelling. Content and discourse analysis were utilised in 15% of the qualitative methods, while

Delphi analysis, bibliometric analysis and cyclone modelling techniques were used in 4% of the qualitative studies.

Table 3. Crosstabulation between Research Methods and Analytical Techniques used in the construction robotics literature.

	Research Methods			
Analytical Techniques	**Quantitative Methods**	**Qualitative Methods**	**Mixed Methods**	**Grand Total**
Analytical hierarchical process (AHP)	0 (0%)	0 (0%)	1 (6%)	1 (1%)
ANOVA	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Bibliometric analysis	0 (0%)	1 (4%)	0 (0%)	1 (1%)
Biomechanical analysis	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Content analysis	1 (1%)	7 (26%)	1 (6%)	9 (8%)
Content and discourse analysis	0 (0%)	15 (56%)	0 (0%)	15 (13%)
Cyclone modelling technique	0 (0%)	1 (4%)	0 (0%)	1 (1%)
Delphi analysis	0 (0%)	1 (4%)	0 (0%)	1 (1%)
Descriptive and process analysis	0 (0%)	0 (0%)	1 (6%)	1 (1%)
Descriptive and statistical analysis	1 (1%)	0 (0%)	1 (6%)	2 (2%)
Descriptive statistics	0 (0%)	0 (0%)	1 (6%)	1 (1%)
Exploratory factor analysis (EFA) and partial least square structural equation modelling (PLS-SEM)	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Fuzzy DEMATEL	0 (0%)	0 (0%)	1 (6%)	1 (1%)
Fuzzy logic and notional analysis	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Graphic computer simulation	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Hierarchical process	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Intercase analysis	0 (0%)	1 (4%)	0 (0%)	1 (1%)
Mathematical modelling and computer simulation	1 (1%)	0 (0%)	0 (0%)	1 (1%)
MoCap analysis	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Modelling	48 (72%)	0 (0%)	10 (56%)	58 (52%)
pre-processing and statistical analysis	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Principal component and correlation analysis	0 (0%)	0 (0%)	1 (6%)	1 (1%)
Scientometric Analysis	1 (1%)	0 (0%)	1 (6%)	2 (2%)
Simulation	5 (7%)	0 (0%)	0 (0%)	5 (5%)
Simulation and Modelling	1 (1%)	0 (0%)	0 (0%)	1 (1%)
Statistical Analysis	1 (1%)	1 (4%)	0 (0%)	2 (2%)
Grand Total	**67 (100%)**	**27 (100%)**	**18 (100%)**	**112 (100%)**

Pearson Chi-square (χ^2) = 134.39 df = 52, $p < 0.001$, Cramer's v = 0.77.

Nonetheless, quantitative methods were the majorly adopted analytical techniques: descriptive and statistical analysis comprised 1% of the quantitative methods, and square structural equation modelling (PLS-SEM) also comprised 1%, along with fuzzy logic and notional analysis, graphic computer simulation, hierarchical process, mathematical modelling and computer simulation, mocap analysis, pre-processing and statistical analysis, scientometric analysis, simulation and modelling and statistical analysis. Simulation, at 7%, was the most-used analytical technique in quantitative methods after modelling, while content analysis was the second-most-adopted analytical method under qualitative methods. The disparity of the distribution produced a statistically significant association between the research methods and the analytical techniques as revealed in the chi-square test of independence (χ^2) (52, n = 112) = 134.39, $p < 0.001$ with a large effect size, Cramer's v = 0.77. The results explain that the reviewed construction robotics articles adhere to the established methodological relationship between the research methods and analytical techniques implemented in a study.

3.13. Relationship between Data Sources and Analytical Techniques Employed in the Construction Robotics and Human–Robot Teams Literature

The variables in Table 4 showing the relationship between data sources and analytical techniques adopted in construction robotics research reveal an uneven distribution. We found that surveys adopted principal component and correlation analysis (25%), EFA and PLS-SEM (25%) and descriptive and statistical analysis (50%). Content analysis was prominent, with studies adopting focus group discussions (100%), project information and literature (100%), expert interviews (67%) and literature (22%). Experimental methods adopted modelling (82%), simulation (6%), pre-processing and statistical analysis (1%) and mocap analysis (1%). Interpretation from a chi-square test of independence showed a statistically significant association between the types of "data sources" and "analytical techniques" used (χ^2) (312, n = 112) = 761.58, $p < 0.001$ with a large effect size, Cramer's v = 0.75. Accordingly, we rejected the null hypothesis in favour of an alternative hypothesis: particular data sources lend themselves to specific analytical techniques, and construction robotics literature has tended to follow this established methodological relationship.

3.14. Relationship between Research Methods and Data Sources Employed in the Construction Robotics and Human–Robot Teams Literature

Table 5 shows the relationship between research methods and data sources employed in the literature of construction robotics and human–robot teams. We found that some data sources such as surveys (50%) were used for specific research methods such as quantitative methods. Similarly, this applied to qualitative methods, as data sources such as literature and expert interviews (100%) and expert interview (67%) were adopted in qualitative methods. Surprisingly, the results also reveal that some data sources were not uniquely associated with specific research methods. This can be seen in experiments being adopted in quantitative (86%) and mixed methods (14%), focus group discussions adopting quantitative methods (100%) and literature reviews adopting quantitative (13%) and qualitative (87%) methods. Using a chi-square test of independence, we found a statistically significant association between the types of "data sources" and "research methods" used (χ^2) (24, n = 112) = 139.39, $p < 0.001$ with a large effect size, Cramer's v = 0.78. Thus, the null hypothesis that there was no statistically significant association between research methods and data sources was rejected. This result is surprising as a similar analysis conducted by [1,57] found no statistically significant association between research methods and data sources. This implies that construction robotics research largely adheres to the established relationship between research methods and data sources compared to some fields in built environment research. This is in line with what is popularly acknowledged in the scientific field: a strong association exists between research methods and data sources. This finding upholds research rigour in construction robotics and demonstrates methodological discipline in addressing research objectives.

Table 4. Crosstabulation between data sources and analytical techniques used in the construction robotics literature.

	Data Sources													
Analytical Techniques	**E**	**E + O**	**EI**	**FD**	**L**	**L + B**	**L + EI**	**L + EI + FG**	**O**	**PI**	**PI + L**	**S**	**SLR**	**Grand Total**
Analytical hierarchical process (AHP)	0 (0%)	0 (0%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
ANOVA	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Bibliometric analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Biomechanical analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Computational fluid dynamics (CFD) simulation	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Content analysis	0 (0%)	0 (0%)	2 (67%)	1 (100%)	5 (22%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (100%)	0 (0%)	0 (0%)	9 (8%)
Content and discourse analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	12 (52%)	0 (0%)	1 (33%)	0 (0%)	1 (100%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	15 (13%)
Cyclone modelling technique	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Delphi analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Descriptive and process analysis	0 (0%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Descriptive and statistical analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (50%)	0 (0%)	2 (2%)
Descriptive statistics	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
EFA and PLS-SEM	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (25%)	0 (0%)	1 (1%)
Fuzzy DEMATEL	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Fuzzy logic and notional analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Graphic computer simulation	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Hierarchical process	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)

Table 4. *Cont.*

	Data Sources													
Analytical Techniques	**E**	**E + O**	**EI**	**FD**	**L**	**L + B**	**L + EI**	**L + EI + FG**	**O**	**PI**	**PI + L**	**S**	**SLR**	**Grand Total**
Intercase analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Mathematical modelling and computer simulation	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
MoCap analysis	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Modelling	58 (82%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	58 (52%)
Pre-processing and statistical analysis	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Principal component and correlation analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (25%)	0 (0%)	1 (1%)
Scientometric analysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (100%)	2 (2%)
Simulation	4 (6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	4 (4%)
Simulation and modelling	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
statistical analysis	1 (1%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (2%)
Grand Total	71 (100%)	1 (100%)	3 (100%)	1 (100%)	23 (100%)	1 (100%)	3 (100%)	1 (100%)	1 (100%)	1 (100%)	1 (100%)	4 (100%)	1 (100%)	112 (100%)

Pearson Chi-square (χ^2) = 761.58, df = 312, $p < 0.001$, Cramer's v = 0.75. E: experiment; E + O: experiment and observation; EI: -expert interview; FD: field data; L: literature; L + B: literature and brainstorming; L + EI: literature and expert interviews; L + EI + FG: literature, expert interview and focus group; O: observation; PI: project information; PI + L: project information and literature; S: survey; SLR: systematic literature review.

Table 5. Crosstabulation between the type of research methods and the types of data sources employed in employed in Construction Robotics and Human–robot teams Literature.

	Data Sources													
Research Methods	**E**	**E + O**	**EI**	**FD**	**L**	**L + B**	**L + EI**	**L + EI + FG**	**O**	**PI**	**PI + L**	**S**	**SLR**	**Grand Total**
Mixed	10 (14%)	1 (100%)	1 (33%)	0 (0%)	0 (0%)	1 (100%)	0 (0%)	1 (100%)	0 (0%)	0 (0%)	1 (100%)	2 (50%)	1 (100%)	18 (16%)
Qualitative	0 (0%)	0 (0%)	2 (67%)	0 (0%)	20 (87%)	0 (0%)	3 (100%)	0 (0%)	1 (100%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	27 (24%)
Quantitative	61 (86%)	0 (0%)	0 (0%)	1 (100%)	3 (13%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (50%)	0 (0%)	67 (60%)
Grand Total	71 (100%)	1 (100%)	3 (100%)	1 (100%)	23 (100%)	1 (100%)	3 (100%)	1 (100%)	1 (100%)	1 (100%)	1 (100%)	4 (100%)	1 (100%)	112 (100%)

Pearson Chi-square (χ^2) = 139.39, df = 24, $p < 0.001$, Cramer's v = 0.78. E: experiment; E + O: experiment and observation; EI: -expert interview; FD: field data; L: literature; L + B: literature and brainstorming; L + EI: literature and expert interviews; L + EI + FG: literature, expert interview and focus group; O: observation; PI: project information; PI + L: project information and literature; S: survey; SLR: systematic literature review.

4. Discussion

This study set out to assess the nature of research methods in construction robotics and human–robot teams research. The findings are discussed below under subthemes.

4.1. Evolution of Construction Robotics Research and Key Thematic Areas

The first question in this study sought to map out the evolution of research publications over the years and discovered low research output in construction robotics compared to other research fields in the built environment, such as sustainable development, project management, building information and modelling, etc. In all publications reviewed, a high concentration were published in Automation in Construction, which originated 45% of the articles, showing how this journal emerged prominently in publishing quality output on construction robotics. A possible explanation for the low output in construction robotics and the concentration of publications in specific journals is low expertise in the field and slowly emerging interest in this area by researchers. The low interest in this area has previously been ascribed to the challenge and perception of robotics as able to replace human workers, in addition to the shortage of funding due to the high cost needed to conduct research in this area and the view of the design implications of using robots in an unstructured workplace like the construction environment [58–60]. However, the spike in research interest post-COVID-19 has possibly encouraged the discussion of construction robotics as vital to achieving construction resilience during shocking events; this is proof that despite concerns about job loss, the value-adding benefits of adopting construction robotics makes it inevitable. Studies are therefore beginning to take these variables into account by focusing on how humans can collaborate with robots on site, what this portends for the nature of work in the built environment, how to mitigate safety risks, enable trust in these systems and minimize the incidence of job loss while also improving opportunities and maximizing the productivity offered by construction robotics. Regarding the types of research papers, research clusters and notable construction robotics publications, it is somewhat surprising that the most cited work [30] is a review paper on the "future of construction automation: Technological disruption and the upcoming ubiquity of robotics". However, this is not contrary to popular knowledge in research that reviews are often the most cited forms of research. The results further indicate that 20 studies have adopted a mix of reviews and original research outputs, which all have considerable relevance to the advancement of robotics research. However, the emergent clusters are disappointing as they reflect low research clusters, signifying the concentration of studies in specifically developed economies. With this in mind, studies must be encompassing to advance expertise, accelerate design and development and improve the capabilities of robotics to improve productivity and eliminate safety risks. The key thematic areas we identified are highlighted in Appendix A.

4.2. Types of Research Methods Employed in the Construction Robotics and Human–Robot Teams Literature

It was hypothesized that there was an equal distribution between any paired components of the research methodologies, and thus any test of association should result in no statistically significant association. Additionally, for the components of the research methods initiated in construction robotics research to match the relationships between the components of the research methods, there must be a statistically significant correlation between the components. Previous studies' findings that strongly debated the predominance of positivistic ontologies in construction research and surfaced doubts on whether it has been rightly applied to addressing research objectives spurred the need for this study [1,15]. When the research methods adopted in a field are doubted in their ability to address research objectives, it affects the relevance of research studies to contribute to industry growth and pedagogical development. The thematic research area of construction robotics and human–robot teams focuses not only on the design and development of robots, but also on the human factors and social issues regarding their adoption. However, care must be taken to ensure that the fad is not blindly adopted with regard to addressing research objectives by adopting quantitative methods solely to move with the times. Still, research objectives continue to be addressed based on best-fit research designs. The prevalence of predominant methods as observed also raises questions regarding whether innovative approaches are being developed and considered in addressing construction robotics research in the built environment. For example, the strength of surveys lies in being highly generalisable if they are based on probability sampling [16], as well as in being able to produce highly reliable measures. This makes surveys valuable as a practical method of obtaining human factor data in robotics [55]. However, further methods could address these objectives even better.

As argued by [56], not using best-fit approaches in research methods to address study objectives also affects policies and policymaking, as it provides a narrow conception of complex realities in the studied area. In addition, the reliance of academic research on external sources for funding has always raised ethical issues when certain methods are favoured for conforming to funders' preferences rather than for being best-fit approaches. While some bias and subjectivity can be eliminated, in reality, not all can be resolved and sometimes the degree of validity achieved from applied methods is damaged. The authors also pointed out that researcher biases are not eliminated by focusing on a narrow research approach. These critical debates and issues spurred the need to conduct this study.

On the use of different research methods, our study revealed that the quantitative approach was the most adopted at 67%, followed by the qualitative approach at 27% and the mixed method at 18%. Though this is contrary to the suggested dominance of qualitative methods as indicated by [5], the result is not surprising given the nature of research in construction robotics. Secondly, it is also encouraging to see an emerging increase in the adoption of qualitative approaches and mixed methods over the years, which affirms that methodological diversity and shift are gaining ground. While the focus should always be on best-fit methods to address research objectives, the growing hybridisation in different research components shows that authors are not merely moving along with the times in adopting quantitative approaches, but adopting methods that fit. This is further supported by [1], who interpreted the diversity as authors realising the benefits of integrating research designs, data sources and analytical techniques from quantitative and qualitative methods.

The debate over research methodologies in construction, engineering and management (CEM) literature is well-established. However, construction robotics studies are challenged by a lack of clear research methodologies and the conflation of data sources, types and analytical techniques inherent in many studies. Research in the AEC sector has predominantly been dominated by the quantitative approach since the 1990s; only 8.4% of studies surveyed completely employed qualitative approaches as recently as 2007 [5]. Ten years later, a review of research methods of 4166 articles spanning from 2000 to 2017 revealed multi-epistemologies in construction research. It was pointed out by [61] that multimethodological perspectives on a problem should be adopted whenever possible and practical, as they are capable of generating more holistic understandings of the phenomena in practice and comprehensive illuminations of those phenomena.

While the quantitative approach is still the main method, mixed approaches and qualitative methodologies are frequently used [5]. However, this is not surprising; in a 1997 study, Runeson reported that the dominance of quantitative methods is congruent with the fact that construction as a field was founded on the pure sciences. In recent years, these claims have evolved given the expansion of construction studies to involve management themes, adopting methods from the social sciences in using quantitative and qualitative approaches to contribute to knowledge building [3].

4.3. Use of Theories and Conceptual Frameworks in Construction Robotics Literature

Another important question in this study was the nature of theoretical and conceptual frameworks in the construction robotics literature. The study revealed that of the 112 articles reviewed, only 7% used a theory/theoretical framework. In contrast, 21% used a conceptual framework/model, though this is not surprising as construction management research, as stated in the studies of [62], has limited usage of theories and concepts. It was previously suggested by [63] that research in the built environment mostly tends towards applied research that aims to solve real-life problems and not discover overarching theories. In contrast to these assertions, [6] argued that using theory aids in faster and simpler understanding of disciplines to simplify complex ideas, norms and relationships in a particular aspect or phenomenon. Built environment researchers who rely solely on theory to organise and analyse data, without emphasizing the need for new theories or the need to challenge existing theories, risk stifling research that is exploratory and makes no immediate impact [1]. Given the need to collaborate between humans and robots in industrialised construction, it becomes imperative that theory is engaged to support the human, organizational and social factors in robotics adoption. As people are at the centre of technology and there exists a call to make technology human-centred [64], robotics research must transcend being perceived as just an "object" research and engage enriching philosophical worldviews where human considerations are at the centre of robotics design and advancement. It is important to bear in mind that not adopting this approach only does a great disservice to the acceptance and perceptions of the drive to adopt robotics in construction.

4.4. Research Designs, Data Sources and Analytical Techniques Employed in Construction Robotics and Human–Robot Teams Literature

In the review of published sources to track the volume of output per source, Automation in Construction had 45% of the articles, the Journal of Construction Engineering and Management had 4.5%, the Journal of Building Engineering had 4% and IEEE had 6% as the top publication sources. While journals often adopt a specific focus, publication outlets can improve interests and participation in construction robotics research by undertaking special issues on the aspects of robotics research area related to their publication objectives. It is also encouraging to see major publishing houses have journals dedicated to robotics research. This is vital to improving the research in construction robotics and subsequently enhancing publication output, which is currently low, with small clusters signifying a lack of collaboration and expertise.

To assess what methods are frequently adopted in the thematic areas of construction robotics, we found that automating construction plants, equipment and systems utilised quantitative methods 12% of the time. Quantitative methods also accounted for 17% of robotics design and development, 6% of ergonomics, health, and safety topics and 4% of the studies regarding collision avoidance/site navigation in human–robot teams. Virtual reality and augmented reality are receiving increased adoption in robotics research based on their strength of visualisation, which is vital for digital rehearsals and simulations. The results reflect the nature of research designs in the field, with experimental design the most frequently adopted (54%), followed by systematic reviews at 19%. The results also show hybrid research designs such as experiments and case studies were adopted in 10% of the articles. In contrast, other standalone designs such as experimental modelling, case studies and surveys were adopted in 7%, 5% and 3% of the articles, respectively. Experimental design is imperative to drive advances in construction robotics research due to the nature of robotics design requiring experiments for optimisation. Studies conducted with lab experiments provide the most meaningful support for causal inferences since they allow for the greatest "control" over subjects and experimental conditions. Therefore, lab experiments have the highest internal validity [65]. Other research designs identified were survey and interviews (2%), bibliometric review (2%), interviews (2%), systematic review and survey (1%), focus group and survey (1%), literature and case study (1%), literature review and survey (1%), Delphi survey (1%), experiment and observation (1%) and process analysis (1%). The bibliometric approach was adopted by [38] to map out the research focus of robotics in the built sector using the Scopus database, identified as one of the major academic databases covering scientific fields and frequently adopted by researchers. Other studies have also used the Web of Science. Studies by [20] adopted a mixed-method systematic review using quantitative and qualitative means through a scientometric–bibliometric method coupled with qualitative content analysis to study the literature systematically. This was to avoid the potential bias of the subjective judgment inherent in mono-methods [66].

The findings on stand-alone data sources revealed that sources from experiments were the most adopted, followed by academic literature, surveys and expert interviews. Meanwhile, in the hybrid data sources, literature and expert interviews were the most commonly adopted, followed by project information and literature, experiment and observation, literature, expert interview and focus group discussions and literature and brainstorming. Combining quantitative and qualitative approaches in research design and data collection as a hybrid approach allows for the possibility of examining data convergence or separation in the theory analysis, increasing the validity and reliability of the resultant data and reinforcing fundamental implications. This is supported by [62,67], who argued for hybrid qualitative and quantitative data sources in construction research. Several factors come into play in selecting data sources, including numerous science and scientific paradigms philosophies. However, to examine the research problem holistically, the appropriateness of the data sources are important [68] in addition to querying what the data is meant for, who can adequately provide the data and how best to collect and interpret this data. Inappropriate data sources lead to the recycling of inaccurate phenomena and the wrong interpretation of findings from data.

Construction research is an applied field, and therefore our research should be relevant and useful [61,69,70]. This is further necessary as we may fail to develop approaches that resonate with practice perspectives if our outputs are not useful [15]. A quantitative mono-method was used with a questionnaire survey to assess the applicable safety technologies and the associated enablers in construction projects [71,72]. In research, triangulation, using different but complementary methods to evaluate one hypothesis or finding, can be a useful strategy, particularly when we combine methods with complementary but different strengths and weaknesses [73]. The design and development of construction robotics for adoption on site have raised diverse human issues such as fears and concerns based on the loss of jobs and safety, trust in human–robot teams, team leadership in human–robot collaboration and privacy and monitoring or replacement of humans by robots, amongst other issues [11,12,74] While spurring the need for deeper research into human factors to improve or impede the design and usage of construction robotics on the worksite, these concerns have also necessitated using various social science methods in the robotics research thematic area. This is critical as construction research methodology amongst social science research methods is needed to understand human factors associated with the adoption of construction robotics [73,75]. Using social science methods to answer questions about human interaction with digital technologies is not new [76,77]. It is imperative to consider that while surveys, questionnaires, experiments, ethnographic observation and unobtrusive techniques are valuable tools, the fact that they yield different perspectives reinforces the need to emphasise decisions regarding research design and define concepts and techniques [13,16,78] theoretically. Hence, in analysing analytical techniques, modelling was the most-used analytical approach comprising 58% of the total review and content and discourse analysis was the second-most-used analytical approach. Simulation, descriptive and statistical analysis, scientometric analysis and statistical analysis were also adopted frequently. Simulation affords the privilege of demonstrating how robots interact with construction site elements using physically accurate simulations and real task data. Simulation is imperative as it could correctly imitate the robot in the construction environment, thereby offering valuable insights [79,80].

Based on the null hypothesis postulated in the study, there was an equal distribution between any paired components of the research methodology. We saw that there was unevenness in the relationship. Additionally, there was a statistically significant association between research methods and research design. We found that 48% of quantitative studies employed modelling with no adoption of qualitative methods. In comparison, content and discourse analysis were utilized in 15% of the qualitative methods, while Delphi analysis, bibliometric analysis and cyclone modelling techniques were used in 4% of qualitative studies. The distribution disparity produced a statistically significant association between the research methods and the analytical techniques.

4.5. Nature of the Relationships between Key Components of Research Methods in Construction Robotics and Human–Robot Teams' Literature

On the relationship between data sources and analytical techniques, the study revealed that surveys adopted principal components and correlation analysis (25%), EFA and PLS-SEM (25%) and descriptive and statistical analysis (50%). We also found a statistically significant association between the types of "data sources" and "analytical techniques". Finally, regarding the relationship between research methods and data sources, some data sources such as surveys (50%) were used for specific research methods such as quantitative methods. Similarly, this applied to qualitative methods as well, as data sources such as literature and expert interviews (100%) and expert interview (67%) were adopted in qualitative methods.

5. Implications

5.1. Implications for Academic Research

Research in construction robotics is emerging slowly due to low interest and high expertise needed and knowledge required [81]. This is further complicated given the absence of studies delineating the state of methods in availing what has been adopted and what is possible as well as a lack of knowledge of the relationships between methodological components. Most construction robotics studies only mention methods in passing, and even literature review papers rarely go in-depth to avail deep analysis of the state of methods. Our findings showcase what has been adopted so far, the approaches different thematic areas have taken to using methods in addressing objectives, debates on the strengths and weaknesses of some methods and the relationships between methodological components. This study supports the need to understand that methods should not be adopted merely based on superficial decisions such as what is trendy or assigned but based on what is fit to address the research objectives. Tables 2–4 showcase vital relationships analysed statistically and extend the understanding of methodological paradigms in construction robotics research. Publication outlets can also undertake special issues on construction robotics methodological paradigms to improve debate, while funding could also be directed towards more methodologically focused articles.

In addition, while patterning methods after industrial robotics in the manufacturing sector, construction robotics researchers must also be aware of the ontological and methodological nature of ensuring that the human perspective critical to the construction industry is not eliminated but rather enhanced.

Lastly, as suggested by [1,5], periodic stocktaking by researchers on research methods allows for objective reflections to address how we can enhance methodological paradigms to respond to new realities and do away with uncritical or non-value-adding methods.

5.2. Implications for Construction Robotics and Human–Robot Design and Development

A negative disposition and perception toward the adoption of construction robotics portends an adversarial stance toward the development of construction robotics. While design and development experts can be primarily dedicated to advancing the technical capabilities of robots for the construction industry, social dynamics and human ergonomic concerns reflect the need to consider methodologies from social sciences that are able to aid understanding of social phenomena in robotics research. This can be closely translated to methods not solely focusing on "machines" but adopting encompassing research paradigms to user-centred robotics adoption in the construction industry. Therefore, methods addressing social constructs or perspectives on construction robotics, though currently sparse, are inevitable. Current concerns regarding monitoring and privacy, safety, trust, ergonomics and job loss are critical barriers, and future research areas need appropriate methodological paradigms.

5.3. Implications to Policy Makers and Industry Stakeholders

For policymakers, the study reveals a better understanding of methods from a pedagogical point of view, thereby requiring rethinking current built environment curricula. The sparseness of contributing countries and research outlets demonstrating a lack of expertise further emphasises the need to enhance skills and knowledge transfer in conducting robotics research to aid its rapid advancement in design. Regarding enabling an environment for robotics research, the government may propose an approach that lowers the cost of conducting studies with robotics, in addition to applying incentives to foster the acquisition of equipment and training on robotics development.

6. Limitations and Future Research

While our study has made critical contributions to construction robotics and human–robot teams' literature, there are a few limitations to acknowledge. Firstly, from the exclusion and inclusion criteria focusing on peer-reviewed journal articles published in English from the Scopus database, the scope of the total articles reviewed might be broader if publications in other languages, formats and databases were considered. Scopus was deemed representative for the study as it contains key publication sources of built environment research outlets and has a very wide coverage as indicated in extant review studies. Also, limiting publications to English was considered to eliminate wrong data and bias in lost translation from other languages. Moreso, previous studies have identified the English language as the dominating medium of communication in most built environment journals from which the articles were extracted. However, these limitations suggest future research directions in reviewing extant studies from all academic databases through the lens of an international, multilingual team of researchers. In addition, the articles were limited to journal publications due to the lack of rigour associated with conference publications, books, book chapters and industry reports. Journals were considered sufficient as they are of standardised quality acknowledged by the global scientific community and have input from reputable teams of peer reviewers in the academic environment. Due to the growing nature of academic research, future studies should assess varying degrees of future publications and map the evolution in the relationship between research methods and data sources, analytical techniques, data sources and philosophical paradigms. The emergence of collaborative robot teams requires studies on human factors and the social imperatives of human–robot teams. Future studies must further review the theories and concepts guiding these phenomena and paradigms.

7. Conclusions

This investigation aimed to assess the nature of research methods in construction robotics as well as their components and relationships between their research designs, data sources and analytical techniques. Further insights were offered regarding mapping the evolutions of methods, the nature of publication, publication sources and what this means for the design and development of construction robotics. Quantitative methods were the main research methods adopted, with an emerging usage of qualitative and mixed approaches. Automation in Construction, the Journal of Construction Engineering and Management, the Journal of Building Engineering and IEEE were the top publication sources.

The publication output was low, with small clusters signifying a lack of collaboration in the field. Experimental design was the most frequently adopted design, followed by systematic reviews. The results also show that hybrid research designs such as experiments and case studies were adopted while other standalone designs such as experimental modelling, case studies and surveys were adopted as well. Case studies are essential for robotics research in the built environment. They provide appropriate test cases to demonstrate the viability and feasibility of adopting robotics and ensure safety before interaction with humans on site. As highlighted by [73,82], case studies are commonly adopted in construction management research, with studies often focused on firms, infrastructure projects, systems or environments.

Other research designs identified were survey and interviews, bibliometric review, interviews, systematic review, focus group and survey, literature and case study, literature review and survey, Delphi survey, experiment and observation, and process analysis. On stand-alone data sources, experiments were the most adopted, followed by academic literature, surveys and expert interviews. Meanwhile, in the hybrid data sources, literature and expert interviews were the most adopted, followed by project information and literature, experiment and observation, literature, expert interview and focus group discussions and literature and brainstorming. With analytical techniques, modelling took the lead, followed by content and discourse analysis. Simulation, descriptive and statistical analysis, scientometric analysis, and statistical analysis were also frequently adopted. We also discovered a statistically significant association between research methods and research design as well as a statistically significant association between research methods and analytical techniques. In addition, we found a statistically significant association between the types of "data sources" and "analytical techniques".

Newer approaches to methods can be undertaken, such as interpretive structural modelling in built environment research [64] and quantitative approaches to interpreting qualitative data [16]. As highlighted by [1], the line between what is quantitative and qualitative is thought-provoking, as it is not uncommon for phenomena or data in both approaches to overlap, with one approach used to triangulate the other. Reliance on traditional boundaries has therefore been questioned, with newer approaches being reinvented or rethought; an example is the use of images and videos to elicit awareness of the usage of collaborative robots/robotics [83]. Evidence was presented by [84] that what cannot be evaluated verbally or physically can be measured through imagery and actions. In delineating visual research methods, [85] pointed out that integrating imagery in surveys assists the researcher in asking what is known about the social world and how it is known. This improves the respondents' capacity to respond to queried realities of diverse phenomena. One major drawback of this approach is that images may generate different insights based on questions asked by the respondents [86,87]. This, therefore, requires scrutiny in questioning.

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Appendix A

Table A1. Summary of Overarching Research Questions/Aims/Objectives and thematic areas.

S/N	Thematic Areas	Summary of Overarching Research Questions/Aims/Objectives	Authors
1	Automating construction plants, equipment and systems	How do we enable autonomous sensing and modelling of construction objects, tasks and processes?	[41,88–91]
2	Robotics design development/production	What design solutions are viable and needed for human–robot collaboration?	[34,35,43,44,92–95]
3	Task planning	What design factors and advances are needed for robot actions in complex assembly tasks and task planning? How does the nature of the task affect the positioning and movement of robots?	[31,96–98]
4	Robotic prefabrication system	How can prefabrication disassemble and reassemble construction robotics with little to no human intervention? What are the needed prefabrication design strategies for geometrically complex building elements?	[99–104]
5	Ergonomics, health and safety	What are the design and ergonomics factors to consider in ensuring the safe collaboration of humans with robotics? How to improve construction safety using emerging technologies such as robotics? What are the health and safety impact of construction robotics in collaborative teams with human workers? What are the physiological and psychological effects of wearables, exoskeletons and robotics on human workers?	[45–47,72,92]
6	Team collaboration/human–robot teams	What design, system and process are needed to integrate robotics successfully and efficiently with human collaboration on-site? What are the management strategies for ensuring safe and effective collaborative teams on construction sites?	[51,105,106]
7	Trust and perception	How can design developments improve trust in safe usage and capability of construction robotics? How do construction workers perceive robots in collaborative teams? Perceptions of future construction robots for buildings.	[42,107–109]
8	3D printing/additive manufacturing	How do we optimise the use of 3D printing for construction robotics?	[9,33,110]
9	Performance of operators	What behavioural issues are associated with integrating human workers with robots in construction?	[111]
10	Collision avoidance/site navigation in human–robot teams	How can robots and workers manoeuvre sites better and without collision? What are design considerations imperative in planning paths in no-walk and walk scenarios?	[48,50,52,112,113]

Table A1. *Cont.*

S/N	Thematic Areas	Summary of Overarching Research Questions/Aims/Objectives	Authors
11	Review studies	What are the past and current developments in construction robotics and implications for future developments?	[30,36,88,114]
12	BIM integration	How do we optimise and integrate BIM/digital twins for construction robotics on-site management? How do we incorporate robot task planning and create detailed motions while conducting construction tasks?	[115–117]
13	Control systems/data fusion	How do we optimise control systems and data fusion for more enhanced robotic applications?	[32,118]
14	Human factors in collaborative robot teams	What are the sources and reasons for human resistance towards construction robotics and collaborative teams? What are the human factors critical to the successful adoption of construction robotics?	[119,120]
15	Cost, barriers, opportunities and benefits	What are the critical barriers the construction industry faces in adopting robotics? What are the benefits construction robotics contributes to infrastructure delivery? How do we develop highly effective and low-cost robots/robotic applications for the construction industry? What opportunities do construction robotics offer in sustainable construction and resilient infrastructure delivery?	[110,120–126]
16	Adoption and implementation	What are the enabling factors and critical drivers for adopting construction robotics? What factors can influence the technological transformation of construction through the adoption of robotics?	[8,127–131]
17	Education, reskilling, learning and training programs	What tools can be adopted in the construction robotics-related reskilling and training of human workers? What is the role of training and pedagogy in adopting and accepting construction robotics? What are in-depth courses on construction robotics and human–robot teams vital in the AEC curriculum to prepare students for industrialised construction?	[59,132,133]
18	Virtual Reality, Augmented Reality and Mixed Reality in Robotics	Applications of virtual reality, augmented reality and mixed reality in robotics simulation, testing, experimentation and research	[39,111,115]

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