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ADVANCES IN HUMAN-ROBOT COLLABORATION (HRC) IN CONSTRUCTION 5.0 FOR BUILDING CONSTRUCTION: A BIBLIOMETRIC AND SYSTEMATIC LITERATURE REVIEW

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SUMMARY: *Construction, characterized by its inherent risks, demands innovative solutions to ensure the safety and efficiency of processes. Human-robot collaboration (HRC) emerges as a promising alternative in this context, especially within the framework of Construction 5.0. However, existing research presents gaps in the comprehensive understanding of the advances and future potential of this synergy. This study addresses this gap through a systematic review of 181 articles published between 2013 and 2024, using a methodology that combines quantitative and qualitative analysis. The results, obtained through an exhaustive literature search and data visualization tools, reveal emerging trends in HRC research within the building sector. In addition, it delves into three key areas of progress: the development of AI-assisted classification systems to improve efficiency in specific tasks, the exploration of robots with emotional capabilities for more flexible adaptation to work environments, and virtual reality training to optimize human-robot collaboration. In addition, three future lines of research are proposed to further explore HRC in the building sector. This research significantly expands the existing knowledge on this topic, placing it at the forefront of the discipline. It also provides practical guidelines for construction professionals to adopt the principles of Construction 5.0, enabling them to address the complex challenges of construction more effectively.*

KEYWORDS: *Human-robot, Collaboration, Construction 5.0, Building Construction, Construction Industry.*

REFERENCE: *Gonzalo Garcés (2025). Advances in Human-Robot Collaboration (HRC) in Construction 5.0 for building construction: A bibliometric and systematic literature review. Journal of Information Technology in Construction (ITcon), Special issue: 'Construction 5.0', Vol. 30, pg. 1244-1276, DOI: 10.36680/j.itcon.2025.050*

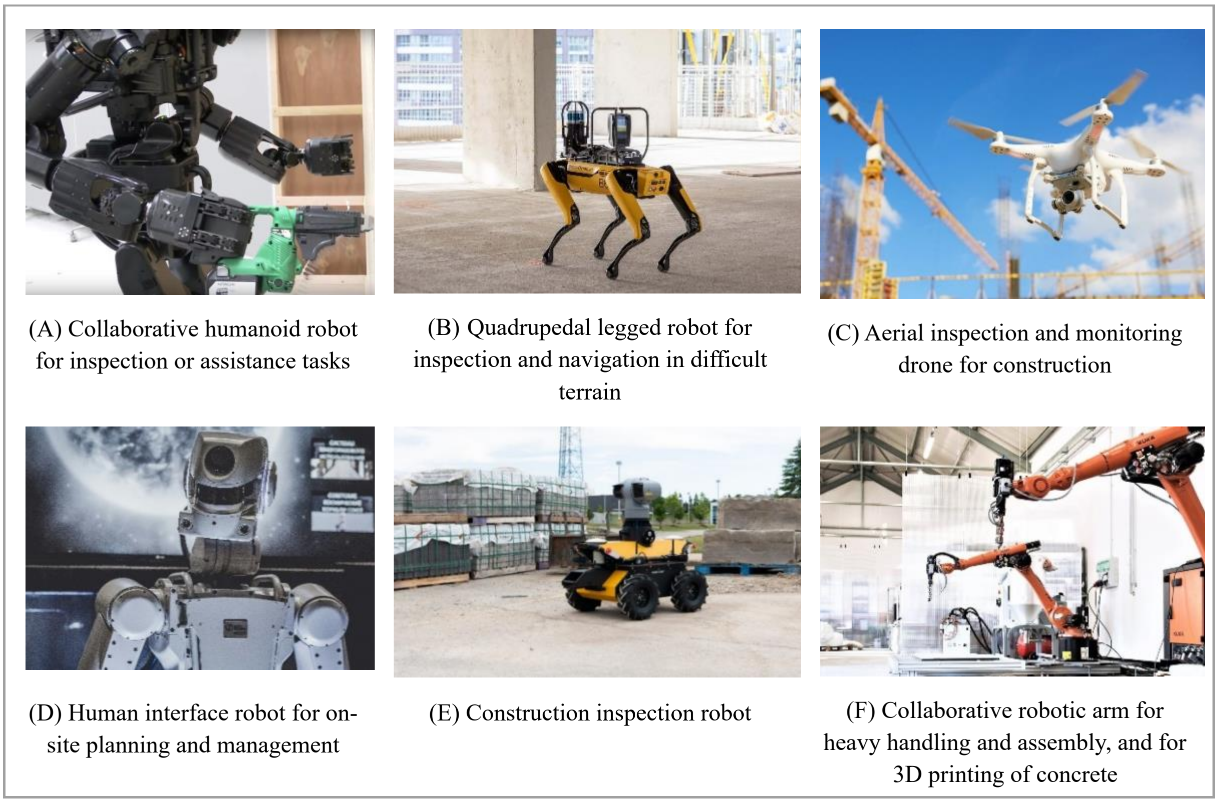
1. INTRODUCTION

The fifth industrial revolution, which has given rise to Construction 5.0, proposes a synergy between human innovation and the precision of advanced technologies, such as artificial intelligence, to address the inherent complexity of construction projects (Ikudayisi et al., 2023; Marinelli, 2023). This merger aims to streamline processes, enhance efficiency and foster creativity in a traditionally labour-intensive sector. The construction industry faces several complex challenges, including a shortage of skilled labour, increasing project demand, the need to improve workplace safety and pressure to build more sustainably (Abioye et al., 2021; Adekunle & Jha, 2024; Kim et al., 2020). These problems have driven the search for innovative solutions. Human-machine collaboration, or HRC, is emerging as a promising answer, offering the possibility of combining the intelligence and adaptability of humans with the precision and strength of machines to improve efficiency, safety, and quality in construction processes (Kattel et al., 2020; Ohueri et al., 2024; Wei et al., 2023).

Due to the growing demand for construction, there has been a need for sustainable and efficient alternatives (Chang et al., 2016; Nardo et al., 2020). Studies highlight the environmental and social benefits of these practices, highlighting their potential to mitigate climate change and promote a circular economy (McBride, 2021; Renteria & Alvarez-de-los-Mozos, 2019; Rinaldi et al., 2023). However, despite its advantages, building construction remains a laborious and complex process that requires significant human intervention (Saavedra et al., 2025; Zhuang et al., 2020). In this context, the integration of robotics into construction processes, promoting HRC, emerges as an innovative strategy to optimize tasks and address the multifaceted challenges of the construction industry. HRC initially emerged in industrial environments, where the integration of automated systems and human labour sought to optimize processes, ensure safety, and increase productivity (Al-Sabbag et al., 2022; Kattel et al., 2020). With technological evolution, especially in the field of artificial intelligence, HRC has transcended its industrial origin, expanding into more complex sectors such as construction (Frank et al., 2019; Wei et al., 2023). This change has been driven by the vision of Construction 5.0, which promotes collaboration between humans and robots as a synergy to improve efficiency and safety in dynamic and unstructured work environments (Bard et al., 2016; Pizoń & Gola, 2023). In this context, robots take on repetitive and potentially hazardous tasks, complementing human skills and enabling greater precision in operations such as dismantling and sorting materials (J.-M. Li et al., 2023; Nardo et al., 2020).

The integration of robotics and artificial intelligence in Construction 5.0 allows for a redistribution of tasks, delegating repetitive and dangerous tasks to robots, while humans focus on activities that require higher cognitive skills (J.-M. Li et al., 2023). This human-robot collaboration (HRC) facilitates real-time decision-making, thanks to the ability of robots to adapt to dynamic environments and provide updated information to operators. In addition, HRC makes it possible to address unforeseen situations more efficiently, taking advantage of the complementary strengths of both agents and contributing to the construction of safer and more sustainable infrastructures. Collaborative construction is enriched by a diversity of robots working alongside humans. For example, humanoid robots capable of performing human-like tasks to complex ones such as panel installation, handling hazardous materials, or cleaning in unstable areas (C. Yang et al., 2024), as well as unmanned ground vehicles (UGVs) that transport materials on construction sites (X. Li et al., 2023). Furthermore, unmanned aerial vehicles (UAVs) offer an aerial perspective for inspections and monitoring (Peschel & Murphy, 2013), while robotic arms perform precise handling tasks (C. Yang et al., 2022) (see Figure 1). In addition, human intellectual assistance plays a crucial role in monitoring and programming these robots, optimizing their performance and ensuring safety in the workplace (Pacaux-Lemoine et al., 2017). This synergy between humans and machines redefines construction processes, increasing efficiency and precision in project execution.

The increasing exploration of HRC in the built environment has been driven by the potential for seamless systems. Recent studies have investigated diverse applications of robotics in construction, from modular manufacturing and waste management to robot-assisted construction on concrete facades and walls (Garcés, García-Alvarado, et al., 2025; J.-M. Li et al., 2023; Ohueri et al., 2024; C. Yang et al., 2024). While these investigations show a growing interest in the integration of robots in construction processes, there is a notable lack of studies focused specifically on the design of HRC protocols for building construction in the context of Construction 5.0. Therefore, further research is required to fully understand the effectiveness, advances and future possibilities of HRC protocols in this field (Feng et al., 2015; Gharbia et al., 2020), in order to fully exploit the potential of human-robot collaboration in construction.



(A) Collaborative humanoid robot for inspection or assistance tasks

(B) Quadrupedal legged robot for inspection and navigation in difficult terrain

(C) Aerial inspection and monitoring drone for construction

(D) Human interface robot for on-site planning and management

(E) Construction inspection robot

(F) Collaborative robotic arm for heavy handling and assembly, and for 3D printing of concrete

Figure 1: Collaborative robots for construction.

Research into the integration of HRC into construction processes is still at an early stage. The scarcity of comprehensive studies addressing emerging challenges in this field leaves a significant knowledge gap. Consequently, fundamental questions remain regarding current trends, best practices, and future research directions in the application of HRC to building construction. Therefore, this research seeks to answer the following questions:

1) What are the latest research trends in HRC in building construction?

2) What are the cutting-edge practices of HRC in building construction?

3) What are the future directions and open problems for HRC in the building construction process?

In order to answer the research questions raised and to provide an updated overview of the most innovative and efficient strategies to integrate HRC into building construction processes, a comprehensive mixed literature review has been conducted. This study covers the last decade (2013-2024) and combines a quantitative analysis, based on bibliometrics and visualized using VOSviewer, with a more in-depth qualitative review. Bibliometrics ensures the objectivity and reliability of the results by synthesizing a wealth of information on the current state of research in HRC in construction. Based on this analysis, several trends and knowledge gaps have been identified, which have been examined in detail, focusing on three key areas: virtual reality training, artificial intelligence-assisted classification, and emotional robots. Finally, new lines of research are proposed to further enrich this constantly evolving field.

The use of a mixed literature review is a superior and highly appropriate methodological approach for this study (Harden & Thomas, 2010a; Snelson, 2016), as it allows for a holistic and robust understanding of the state of HRC integration in construction. Unlike a purely qualitative or quantitative review, this hybrid method integrates the objectivity and breadth of bibliometric analysis with the contextual depth of a qualitative review (Guo & Feng, 2019). Quantitative analysis, facilitated by tools such as VOSviewer, provides a systematic and rigorous view of research trends, key collaborations, and knowledge gaps across a vast database of publications (Harden & Thomas, 2010a; N. Van Eck & Waltman, 2010). This ensures a solid empirical basis and minimizes the bias inherent in manual reviews (Alaloul et al., 2022; N. Van Eck & Waltman, 2010, 2014). Furthermore, the qualitative review enriches these data with a detailed and contextualized examination of innovative strategies, such as virtual reality training and emotional robots, that bibliometrics alone could not unpack with the same level of depth (Snyder, 2019). Consequently, the combination of both approaches not only ensures the validity and reliability of the findings (Guo & Feng, 2019; H. Liu et al., 2021), but also offers a holistic and detailed understanding, crucial for proposing future and relevant lines of research in such a dynamic and multidisciplinary field.

That said, the construction industry, traditionally characterized by laborious and risky processes, is at a turning point thanks to the emergence of Construction 5.0. HRC emerges as a fundamental pillar in this transformation, offering the promise of revolutionizing construction processes (Gharbia et al., 2020; Wei et al., 2023). This article explores the potential of HRC to optimize building construction, detailing recent developments in the field and outlining promising future research directions. By merging human dexterity with robotic precision, HRC paves the way to safer, more efficient, and more sustainable construction projects. The findings of this research are presented as a valuable guide for construction automation researchers, providing guidelines for the application of contemporary HRC practices in the building sector. Furthermore, in line with the principles of Construction 5.0, this study offers a practical framework for construction professionals to effectively integrate human-centered approaches with emerging technologies, such as AI-driven robotics, to address the evolving challenges of the sector.

2. METHODOLOGY

This study examined human-robot collaboration in construction using a three-stage methodology that combined a quantitative bibliometric analysis with a qualitative review. Initially, a systematic review was conducted to identify gaps in the literature and understand the conceptual interactions between human-robot collaboration within the framework of Construction 5.0 and construction. Subsequently, a bibliometric and social network analysis was conducted to assess publication trends and map key conceptual relationships, analysing relevant publication metrics and discussing key concepts (Garcés, Forcael, et al., 2025; Harden & Thomas, 2010b; Oraee et al., 2017). Finally, the third stage focused on identifying key conceptual connections and the latest technological trends in Construction 5.0 through a qualitative analysis of the discussions. Figure 2 presents the tools, activities and results of each research phase.

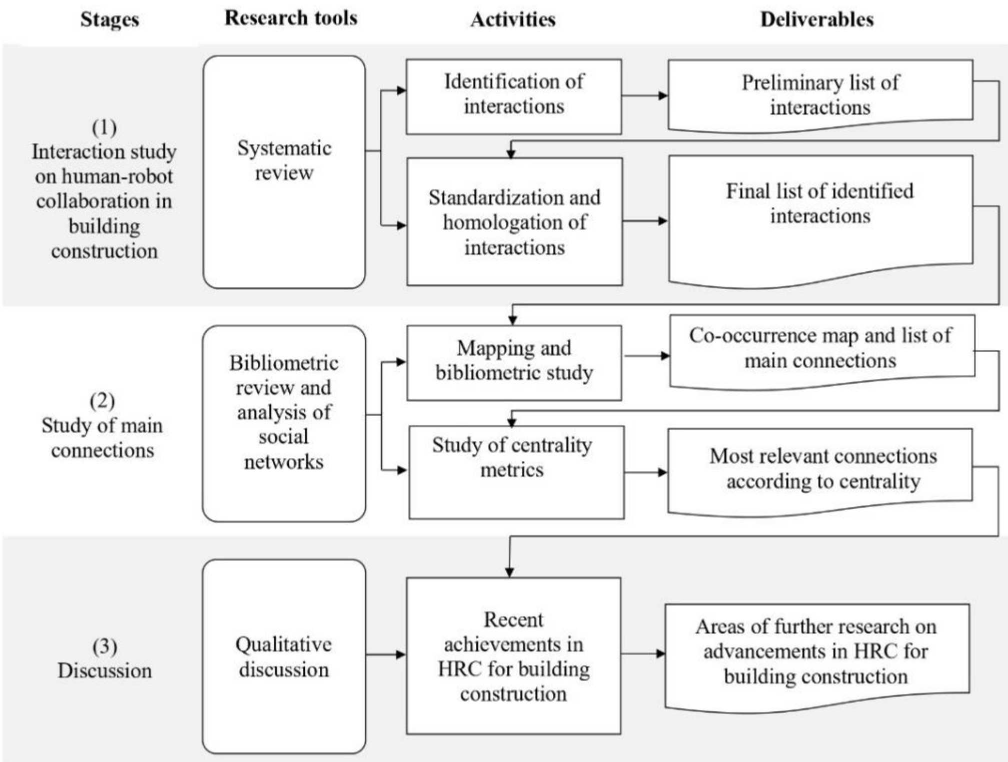


Figure 2: Research Methodology.

Systematic review and bibliometric analysis are two distinct but complementary research tools. On the one hand, systematic review is a rigorous qualitative method that seeks to synthesize existing evidence to identify and classify HRC interactions, ensuring exhaustiveness and minimizing selection bias through a predefined protocol (Moher et al., 2010). On the other hand, bibliometric analysis is a quantitative method that maps the structure and evolution of the field through metrics such as the number of publications, citations, and keyword co-occurrence analysis, which allows to identify emerging trends, key authors, and influential institutions (Ivancheva, 2008). The combination of both methods, as shown in Figure 2, is crucial for this field: the systematic review establishes the conceptual basis and a census of interactions, while bibliometric analysis provides a quantitative context, highlighting the influence and connections between the areas of study (He et al., 2022; J.-M. Li et al., 2023). This dual approach validates qualitative findings and provides a holistic perspective, identifying gaps and promising areas for future research (Guo & Feng, 2019; Yoonus & Al-Ghamdi, 2020), which is critical for the advancement of HRC in construction.

2.1 Stage 1: Interaction study on HRC in building construction — Systematic Review

This systematic review analysed the academic literature on human-robot collaboration, Construction 5.0, and building, following a two-phase methodology: data collection and mapping, and a rigorous analysis according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology (Garcés, Sanz-Benlloch, et al., 2025; Ogunmakinde et al., 2024; Sharma & Laishram, 2024). The article selection process was executed in five sequential stages (preliminary, identification, screening, eligibility, and inclusion), starting with filtering by title, keywords, and abstracts, and subsequently applying exclusion criteria. The eligibility stage involved reading the entire texts to include only those directly relevant to human-robot collaboration in the building construction phase, the flow of which is detailed in the PRISMA diagram in Figure 2.

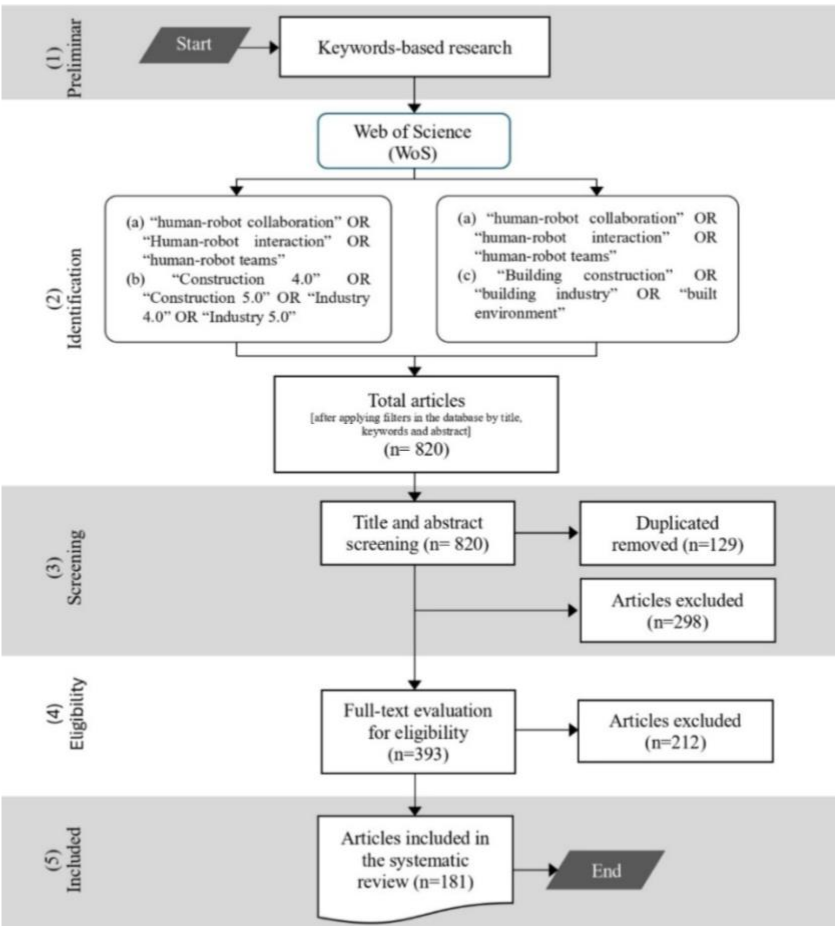


Figure 3: Workflow diagram for data extraction according to the PRISMA methodology.

- The search strategy for this review focuses on the concepts of "Human-Robot Collaboration", "Construction 5.0", and "Building Construction". Articles from the AEC (Architecture, Engineering, and Construction) sector that address the fifth industrial revolution or Construction 5.0 in the construction phase are included. Conversely, publications from other areas such as tourism, manufacturing, automotive, agronomy, healthcare, or education, as well as those not in English, will be excluded. The time period was limited to the last eleven years, a decision justified using similar periods in previous bibliometric studies (Oraee et al., 2017; H. Wang et al., 2019).
- To collect information relevant to research on human-robot collaboration in the context of Construction 5.0, the Web of Science (WoS) database was chosen. This choice is based on its recognized and broad coverage within the field of construction research, considered superior to other similar platforms (Hosseini et al., 2018; Mongeon & Paul-Hus, 2016; N. J. van Eck & Waltman, 2014). Furthermore, WoS stands out for its ability to integrate diverse research disciplines (Mongeon & Paul-Hus, 2016) and for its extensive repertoire of highly reliable periodical publications with impact factors, which ensures the quality of the collected data (Iowa State University, 2023).
- Screening and evaluation of retrieved studies: After applying these criteria, 298 articles were discarded and 129 duplicates were eliminated, resulting in a final corpus of 393 publications. A thorough evaluation of the articles retrieved in WoS was then carried out. Through a manual review of titles, abstracts and full texts, those studies that were closely related to the objectives of this research were selected. This selection process, although laborious, was essential to guarantee the quality and relevance of the documents included in the final analysis (Ly et al., 2024; Ogunmakinde et al., 2024). As a result of this rigorous evaluation, 181 articles were identified that met the established inclusion criteria.

After selecting a sample of 181 publications, a comprehensive bibliometric analysis was conducted. This analysis included an evaluation of publication sources, identification of the most influential authors, determination of the countries with the greatest research activity in the area, the annual distribution of publications, and the creation of a keyword co-occurrence map. The objective of the latter was to discern the central theme addressed and its main conceptual interconnections within the analysed document corpus.

2.2 Stage 2: Study of main connections — Bibliometric review and analysis of social networks

Interactions within the document corpus were visualized through bibliometric networks using VOSviewer software, specifically applying word co-occurrence analysis to identify the most relevant and cited terms. This method, which evaluates the co-occurrence of terms in a text, facilitated the understanding of the conceptual and thematic structure of human-robot collaboration in building construction (Galvez, 2018; Miguel et al., 2018). This analytical phase, focused on key relationships and emerging trends, was divided into two main activities: a geographical and bibliographic study implemented with VOSviewer (Y. Cao et al., 2022; Garcés & Bastías, 2025; N. Van Eck & Waltman, 2010). A bibliographic map was generated based on the co-occurrence and recent trends of the identified primary connections, complemented by frequency tables from the software. Key terms were defined by their high co-occurrence, reflected in the size of the nodes, considering their frequency and their links with other terms. Finally, the main interactions (clusters) and potential synergies were analysed, with a particular focus on the construction sector and human-robot collaboration.

According to the theoretical framework of graph theory, the visualization and analysis of interconnections between key concepts in the literature are fundamental (McKnight, 2014). In the maps generated, the closeness between nodes represents the strength of the conceptual relationship between terms, while the density of links indicates the frequency of co-occurrence of these concepts in the documents (Esser & Fahland, 2021; Golbeck, 2013). The clusters formed closely related thematic groups, revealing the main areas of study. Likewise, the number of connections of each node (degree centrality) and its ability to link different clusters (betweenness centrality) indicate the centrality and influence of specific concepts in the knowledge network, which facilitates the identification of trends and synergies relevant to research (Al Hattab & Hamzeh, 2015; Hickethier et al., 2023).

2.3 Stage 3: Qualitative discussion

To complement the overview of the field of study provided by the bibliometric analysis, a qualitative analysis of the discussions in the selected articles was conducted to explore in-depth the perspectives and nuances of the research. Through an iterative process of coding and comparison, recurring themes, trends, and significant gaps in the literature were identified, with the goal of detecting patterns, links, and emerging challenges in human-robot collaboration in building construction. This process began with a thorough document review to identify the connections or interactions highlighted by the authors. Each interaction was then standardized and categorized with a maximum of five keywords, grouping them into recurring thematic clusters that demonstrated significant connections between concepts or variables. Finally, interactions with shared themes were unified, consolidating a comprehensive bibliographic database. In this context, “interactions” refer to the conceptual links identified in the scientific literature between various terms or concepts related to human-robot collaboration in building construction, which were visually represented in a co-occurrence map where nodes symbolize concepts and lines indicate their co-occurrence frequency.

3. FINDINGS

To obtain an accurate and complete dataset, a triangulation of the results obtained from the keyword and snowball searches was performed, thus eliminating duplicates. This cleaning process resulted in a final corpus of 181 articles retrieved through the keyword search. To provide an overview of the data, a graphical representation is presented in Figure 4, which details the distribution of articles by year of publication, country of origin and document type.

The results presented in Figure 4(a) reveal an exponential growth in scientific production related to human-robot collaboration in construction starting in 2020. A notable increase is observed in the number of annual publications, going from an average of 5 articles between 2016 and 2019 to 58 articles in 2024 (data up to October). This boom in research is also evident in Figures 4(b) and 4(c), where the United States, China and Germany are positioned as the leading countries in terms of several publications and citations, respectively.

Following the preliminary analysis, a bibliometric methodology was applied through VOSviewer to explore research trends in human-robot collaboration in the building sector. Through co-occurrence and co-citation analysis of key terms, knowledge networks were visualized, and the most relevant topics were identified.

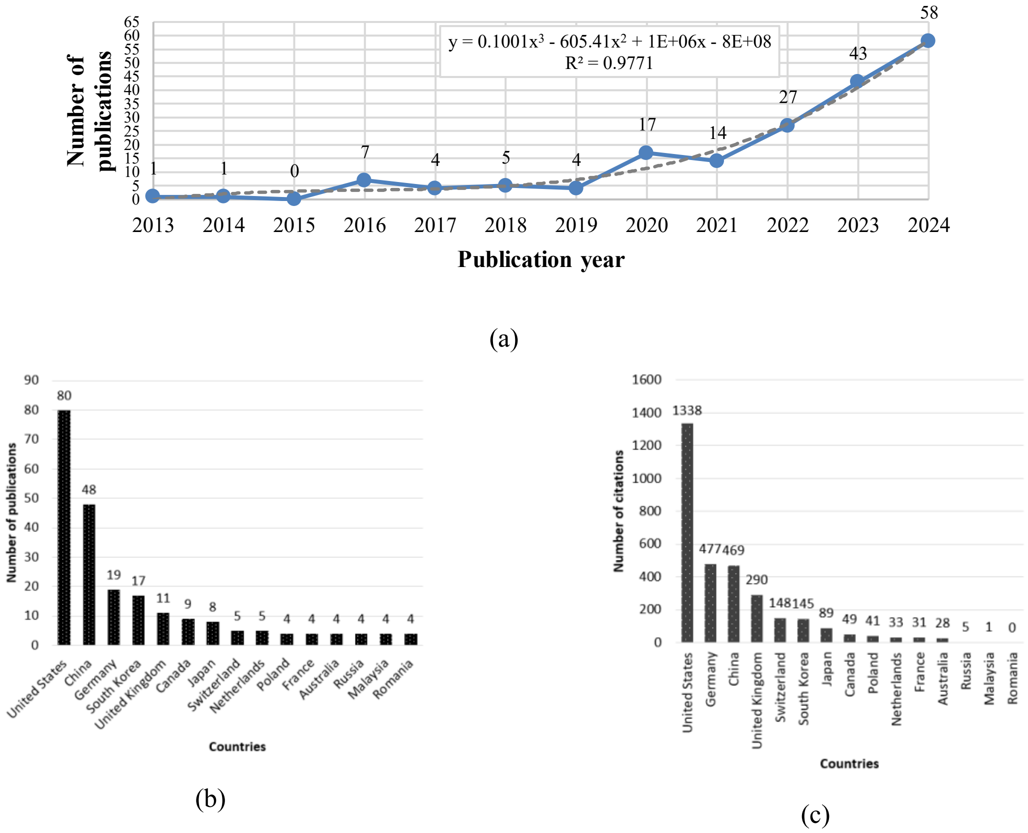


Figure 4: (a) Annual publication in the last decade, (b) Distribution of literature by country, (c) distribution of citations by country.

3.1 Research trend (keyword co-occurrence)

To explore the evolution of HRC research in the construction sector, a bibliometric network analysis was carried out based on the co-occurrence of key terms. Those terms that appeared at least five times in the documentary sample were selected for analysis. The results, visualized in Figure 5, show a network of interconnected concepts, where the size of the nodes reflects the frequency of appearance of each term and the thickness of the edges indicates the strength of the association between them. This graphic representation allows us to identify the central themes, the relationships between them and the less explored areas of research (Al-Ashmori et al., 2020; Choi et al., 2020; N. Van Eck & Waltman, 2010).

Figure 5 presents a visual representation of the conceptual structure of the field of study through a network of keyword co-occurrences. This network, segmented into seven thematic clusters differentiated by colour, allows the identification of the main areas of research and the relationships between them. For a deeper understanding of the relevance of each term, a quantification of the frequencies of appearance of the most significant keywords is presented in Table 1.

Table 1: List of author keyword co-occurrences in HRC.

Keyword	Occurrence	Total Link Strength
Construction robotics	84	199
Human-Robot Collaboration (HRC)	49	168
System	36	146
Automation	25	110
Construction	15	41
Technology	14	64
Construction automation	13	42
Safety	13	58
Model	12	37
Virtual Reality	11	44
Design	10	31
Framework	10	65
Mobile robot	10	19
Teleoperation	10	47
BIM	9	26
Recognition	9	21
Fabrication	8	42
Simulation	8	32
Implementation	7	50
Management	7	34

The results of the bibliometric analysis, presented in Table 1, confirm the prominence of robotics in construction research. The term “Construction robotics” emerges as the most frequent and connected, evidencing the growing interest in this area. However, despite the advances in the implementation of robots in construction, as demonstrated by previous studies (Burden et al., 2022; Y. Liu et al., 2024; Onososen & Musonda, 2023), there is a notable lack of research that explores in depth the challenges and opportunities of Construction 5.0 in the context of HRC. This gap in the literature underlines the need for further study of the benefits and limitations of HRC in building construction, which is the main objective of this research. A more detailed analysis of this gap is presented in Section 4.

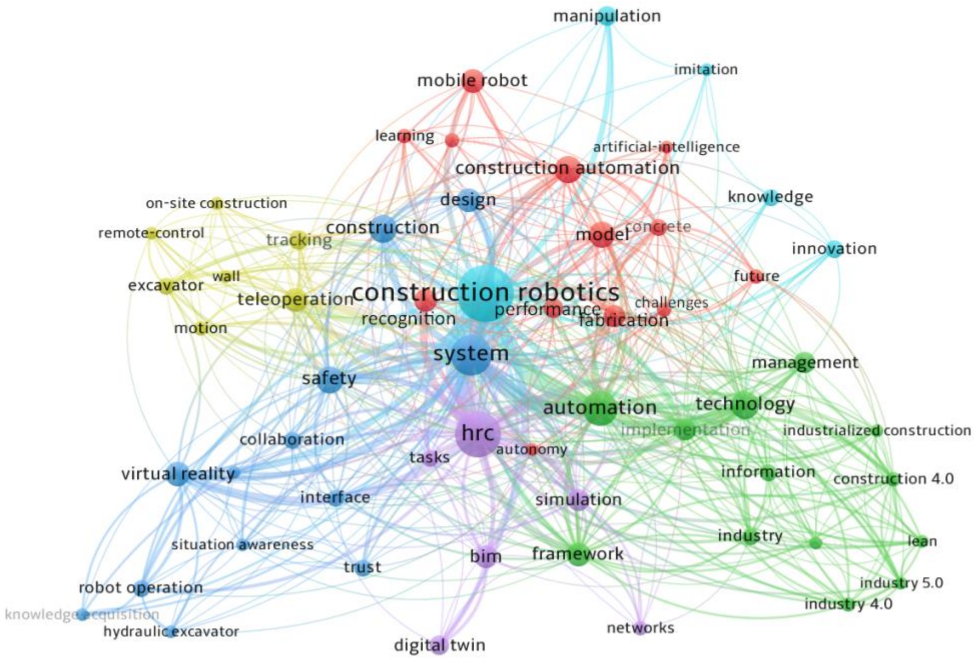


Figure 5: Keyword co-occurrence analysis.

3.2 Co-citation analysis

Co-citation analysis allows you to visualize the connections between key documents, prominent authors, and relevant information sources in a field of study (Cardenas et al., 2024; H. Wu et al., 2024). In this research, this technique was used to map the collaborations between authors and academic institutions that have significantly contributed to research on human-robot collaboration in building construction, and also to observe the connections between academic institutions that have led this line of research.

3.2.1 Co-citation of authors

Co-citation analysis, which reveals the connections between authors through shared references in their papers, is a fundamental tool for identifying the most influential researchers in each field (Safura et al., 2020; Shen et al., 2004). In this study, VOSviewer was used to build an author co-citation network to determine the academic leaders in the area of human-robot collaboration in the building industry. A limit of at least 120 citations was set to ensure the relevance of the authors included in the analysis. The results, presented in Figure 6, show a network of 9 highly connected authors, suggesting possible future collaborations.

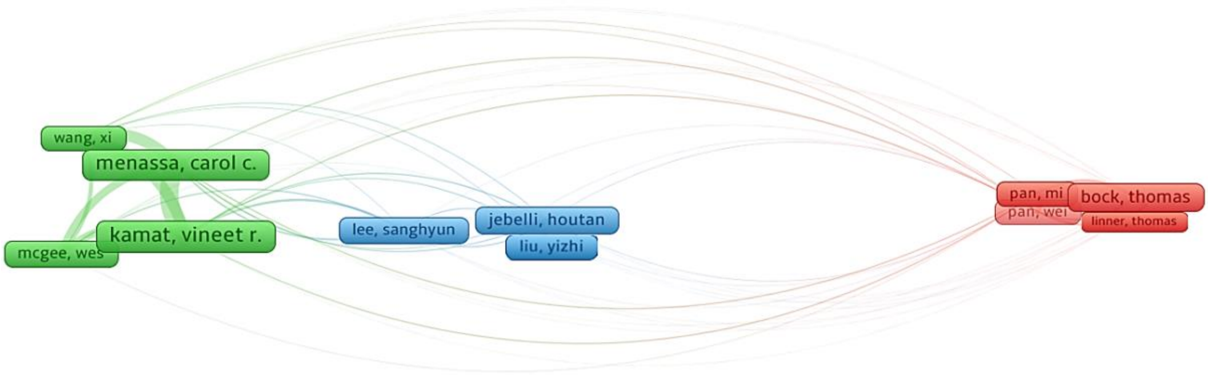


Figure 6: Author co-citation network.

Figure 6 provides a visual representation of the collaboration structure among authors, divided into three distinct groups identified by colours: red, green and blue. These groups, whose details are presented in Table 2, reveal co-authorship patterns that allow characterizing the different research communities within the field.

Table 2: Top 9 most cited authors on HRC in building construction.

Author	Cluster	Documents	Citations	Total Link Strength
Bock, Thomas	Red	9	288	663
Lee, Sanghyun	Blue	6	283	820
Pan, Wei	Red	5	268	1274
Kamat, Vineet R.	Green	14	216	4459
Menassa, C.	Green	12	197	4378
Wang, Xi	Green	5	162	3011
Linner, Thomas	Red	6	154	648
Mcgee, Wes	Green	7	143	2185
Pan, Mi	Red	5	122	1274

According to Table 2, a hierarchical classification of influential authors in research on building construction is observed, where the frequent co-citation of the grouped authors suggests a strong thematic connection between their works, allowing the identification of the most prominent researchers and the most active scientific communities. For example, Bock, Thomas, in the red group, has the most citations, 288, followed by Lee, Sanghyun, in the blue group, with 283 citations. This is followed by Pan, Wei, in the red group, with 268 citations, and then Kamat, Vineet R., in the green group, cited 216 times. These co-authorship data facilitate the identification of the most influential researchers in the field of human-robot collaboration and Construction 5.0, which can guide future collaborative and research efforts.

3.2.2 Co-citation of publishing universities

To identify the leading institutions in research on human-robot collaboration in construction 5.0, a bibliometric analysis was carried out. Table 3 presents the 12 institutions with the highest number of publications in this field, highlighting their significant contribution to the development of knowledge in this area.

Table 3: Top 10 contributing institutions.

No.	Institutions	Country	No. of Publications	Citations	Total link strength
1	University of Southern California	United States	5	350	480
2	Technische Universität München	Germany	10	294	311
3	The Pennsylvania State University	United States	15	224	830
4	University of Michigan	United States	17	206	1926
5	Universität Stuttgart	Germany	7	140	161
6	Hong Kong Polytechnic University	China	5	68	1003
7	Chongqing University	China	5	39	660
8	Texas A&M University	United States	7	35	1185
9	Seoul National University	South Korea	5	23	624
10	The University of Hong Kong	China	10	19	1554

The University of Southern California tops the list with 350 citations and a remarkable link strength of 480, closely followed by the Technische Universität München with 294 citations and a link strength of 311. The University of Michigan, although with fewer citations (206), has the highest total link strength (1926), suggesting denser collaboration with other institutions. Other notable institutions include Pennsylvania State University, the University of Stuttgart, Hong Kong Polytechnic University, Chongqing University, Texas A&M University, Seoul National University, and the University of Hong Kong, each of which contributes significantly to the knowledge network in this emerging field. The network visualization complements the table by graphically showing the interconnections and thematic proximity between these leading universities.

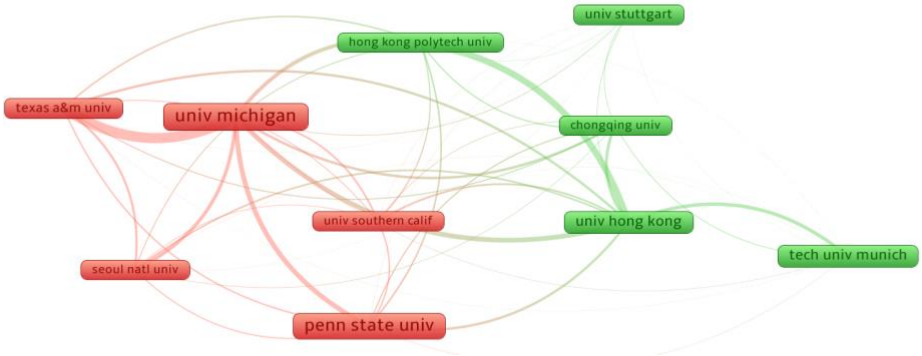


Figure 7: Bibliometric Coupling Network by Institutions.

4. DISCUSSION OF THE FINDINGS OF THE QUALITATIVE REVIEW

This study employed a methodology combining a bibliographic and systematic approach with network analysis using VOSviewer for a deep dive into the field of human-robot collaboration (HRC) in the context of Construction 5.0. In addition to the quantitative findings derived from the bibliometric analysis (2013-2024), a rigorous thematic analysis of the qualitative literature published in the last decade was conducted. This dual strategy facilitated the identification, categorization, and systematic analysis of emerging research trends and topics, culminating in a comprehensive and contextualized understanding of the state of the art in the field. Through iterative coding and constant comparison of qualitative data, it was possible to discern recurring patterns, identify existing knowledge gaps, and outline future research directions, thus consolidating the theoretical and conceptual framework of the study. Based on the above, this section answers the 3 research questions: 1) What are the latest research trends in HRC in building construction?; 2) What are the cutting-edge practices of HRC in building construction?; and 3) What are the future directions and open problems for HRC in the building construction process?

4.1 What are the latest research trends in HRC in building construction?

Industrial evolution, marked by the transition from Industry 4.0 to Industry 5.0, has redefined production paradigms (Habash, 2022; Huang et al., 2022; Ikudayisi et al., 2023; J. Yang et al., 2024). While Industry 4.0 was characterized by digitalization and process automation (Garcés & Peña, 2020, 2022; Ghobakhloo, 2020; Marinelli, 2023), Industry 5.0 focuses on the synergy between human creativity and emerging technologies, seeking to optimize resources and promote sustainability (Adel, 2023; Gürdür Broo et al., 2022; Habash, 2022; Marinelli, 2023). In this context, Construction 5.0 represents an adaptation of these principles to the building industry, promoting collaboration between humans and machines through advanced communication systems (Marinelli, 2023; Ohueri et al., 2024; Yitmen et al., 2023). This new construction era is based on informed decision-making and the integration of innovative technologies, to achieve more efficient, sustainable and resilient construction (Tunji-Olayeni et al., 2024; Yitmen et al., 2023). Construction, a traditionally labour-intensive sector subject to various constraints, is undergoing a transformation process driven by the growing demand for sustainability and efficiency (Murtagh et al., 2020; Sfakianaki, 2015). While efforts to incorporate renewable materials and reduce waste are notable, the industry still faces challenges such as a shortage of qualified labour, the complexity of projects and the need to comply with increasingly stringent regulations (W. Lu et al., 2024; Moradi & Sormunen, 2023; Murtagh et al., 2020; Turner et al., 2021). In this context, human-robot collaboration emerges as a promising solution, offering the possibility of automating repetitive and dangerous tasks, optimizing construction processes, and improving precision in project execution (Ohueri et al., 2024; Onososen & Musonda, 2023). This synergy between humans and machines not only contributes to increasing the productivity and quality of buildings but also allows us to more effectively address the problems associated with building demolition by facilitating the reuse of materials and minimizing waste. Figure 8 concisely presents how the evolution of robotics is redefining collaboration in industry, moving from a “human-led” model to an increasingly “robot-led” one in certain applications. Along this spectrum, we see how robotic exoskeletons support workers by reducing injuries, while collaborative robots assist in the handling of heavy components, improving productivity and accuracy in tasks such as assembly. Mobile robots optimize finishes by efficiently applying materials, and interactive robots replicate complex tasks, accelerating the training of new generations. Moving toward greater autonomy, autonomous drones ensure safe inspections in risky environments, and remote robots handle hazardous materials, eliminating human exposure. Finally, Sorting Robots demonstrate a more autonomous approach by improving waste segregation and recycling rates, paving the way for safer, more efficient, and more sustainable construction through the integration of robotic solutions tailored to each need.

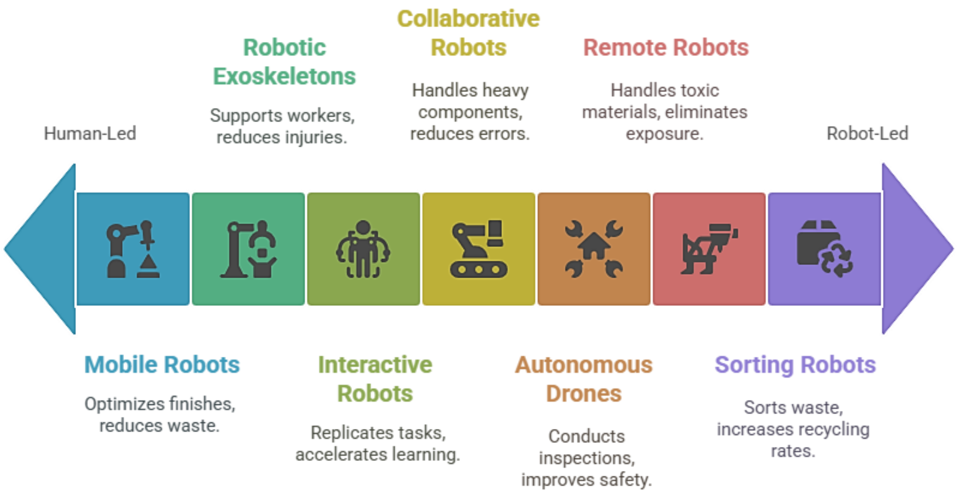


Figure 7: Automation in building construction: from human-led to robot-led task execution.

Construction 5.0, with its focus on human-robot collaboration, offers an innovative solution to address current challenges in the building sector and promote sustainability (Ohueri et al., 2024). The integration of robots equipped with advanced vision systems allows for the automation of dangerous and repetitive tasks, such as waste sorting, thereby minimizing workers' exposure to occupational hazards (P. Sun et al., 2023). Artificial intelligence (AI) also gives these robots the ability to adapt to dynamic environments and learn from human experience, optimizing construction processes and ensuring precision in the execution of tasks (Dimitropoulos et al., 2021; Obaigbena et al., 2024). This synergy between humans and machines accelerates the construction of buildings, improves the quality of the results and contributes to the implementation of more sustainable practices in the sector (Su et al., 2021). The implementation of HRC in construction has proven to be an effective strategy to improve safety, efficiency, and sustainability in the construction sector (Cardenas et al., 2024). Empirical studies show a significant reduction in workplace accident rates thanks to the automation of dangerous tasks, as well as a considerable increase in the precision of processes such as material classification (Liang et al., 2021a; Y. Sun et al., 2023). In addition, the HRC promotes the adoption of circular practices by facilitating the recovery and reuse of construction materials, thus minimizing the environmental impact (Hjorth & Chrysostomou, 2022; T. Wu et al., 2024). By enabling more informed and accurate decision-making, HRC helps reduce costs and errors (Hjorth & Chrysostomou, 2022; Onososen & Musonda, 2023), optimizing construction processes and promoting long-term sustainability in the industry (Rinaldi et al., 2023).

In order to promote the transformation towards Construction 5.0 and optimize construction processes, the academic community has focused its efforts on researching the various facets of HRC. Through a critical review of the existing literature, the main lines of research in this field have been identified and categorized, which are summarized in Table 4. These lines range from the design of intuitive interfaces to facilitate the interaction between humans and robots to the analysis of the social and economic impacts of automation in the building industry.

The interdependence and complementarity between these lines of research are highlighted. Thus, the development of intuitive human-machine interfaces is essential for process automation, while planning and optimization are indispensable for maximizing the benefits of human-robot collaboration (Gervasi et al., 2020; Nourmohammadi et al., 2022; Tonola et al., 2021). However, despite advances in the field of robotics, especially in the context of human-robot collaboration in construction, research is still at a preliminary stage, focused on conceptualization and experimentation, compared to sectors such as manufacturing, automotive and aeronautics. This situation is evidenced by the scarcity of studies exploring the application of cutting-edge technologies in human-robot collaboration to address challenges specific to the construction sector, such as hazardous materials handling, and selective demolition and rescue operations (Callari et al., 2024; Gervasi et al., 2020).

Table 4: Lines of research on HRC in construction.

Studies	Line of research	Goal	Examples	Considerations
(Adami et al., 2022; Cai et al., 2023; Inamura & Mizuchi, 2021; Leng et al., 2023; Okpala et al., 2023; Rodrigues et al., 2023; Rodriguez-Guerra et al., 2021; Shayesteh et al., 2022; Tomori et al., 2024; Yoon et al., 2023; Zacharaki et al., 2020)	Human-Robot Interaction (HRI) in Construction Environments	Study how humans and robots interact safely and efficiently in construction environments, which are dynamic and present diverse challenges.	• Designing intuitive interfaces so that workers can easily control and collaborate with robots. • Developing perception algorithms that allow robots to understand their environment and avoid collisions with workers. • Researching effective communication between humans and robots, including natural language and gestures.	Security, usability, adaptability to different levels of worker experience
(Burden et al., 2022; Fan, 2020; Fu et al., 2024; Kostavelis et al., 2024; Kramberger et al., 2022; D. Lee & Han, 2024; J. S. Lee et al., 2022; Liang et al., 2021b; Simões et al., 2022; X. Wang et al., 2021; Zhang et al., 2023)	Automation of construction tasks and processes	Identify and automate repetitive, dangerous or high-precision tasks using collaborative robots.	• Development of robots for masonry, welding, painting and finishing tasks. • Automation of manufacturing processes for prefabricated components on site. • Use of drones for inspection and monitoring of structures.	Flexibility, scalability, return on investment, integration with project management systems.
(Alenjareghi et al., 2024; Chu & Chen, 2023; M.-L. Lee et al., 2022; S. Li et al., 2024; Liao et al., 2023; Lou et al., 2024; Merikh Nejadasl et al., 2024; Nourmohammadi et al., 2022; Parsa & Saadat, 2021; Pupa et al., 2024; Rega et al., 2021; Tonola et al., 2021; Yu et al., 2021)	Planning and optimizing human-robot collaboration	Develop tools and methodologies to plan and optimize collaboration between humans and robots in construction projects.	• Simulation of work scenarios to evaluate the efficiency and safety of different human-robot team configurations. • Optimization of task sequences and resource allocation to minimize execution times and costs. • Development of robot fleet management systems.	Artificial intelligence, machine learning, combinatorial optimization.
(Baltrusch et al., 2022; Callari et al., 2024; H.-L. Cao et al., 2023; Gervasi et al., 2020; Giallanza et al., 2024a, 2024b; C. J. Lin & Lukodono, 2021; L. Lu et al., 2022; Rinaldi et al., 2023; Simone et al., 2022; Van Wynsberghe et al., 2022; Weiss et al., 2021)	Social and economic impact of human-robot collaboration in construction	Analyse the social and economic consequences of introducing robots in construction, including the creation of new jobs, the improvement of working conditions and the transformation of business models.	• Studies on the acceptance of robots by workers and society in general. • Analysis of the impact of automation on the training and capacity building of workers. • Evaluation of the economic benefits of human-robot collaboration in terms of productivity, quality and cost reduction.	Ethics, equity, public policies, sustainability

Although human-robot collaboration in Construction 5.0 has emerged as a new frontier in the industry, there remains a latent concern among professionals regarding the potential replacement of human labour by automated systems (Gervasi et al., 2020; Simone et al., 2022; Tonola et al., 2021). This concern underlines the urgent need to develop innovative and efficient strategies to integrate HRC into construction processes in an organic manner. Current literature and practice show a notable lack of research in this field. To remedy this lack and address the concerns of professionals, it is essential to offer a comprehensive and forward-looking vision of the development of HRC in the built environment, with special emphasis on construction. In the context of the transition towards Construction 5.0, it is essential to promote a synergistic interaction between robots and human intelligence to deal with the complexities inherent to construction (Callari et al., 2024; Gervasi et al., 2020; Obaigbena et al., 2024), optimizing productivity, mitigating risks, and promoting sustainable practices.

4.2 What are the cutting-edge practices of HRC in building construction?

To present an accurate overview of the advances in human-robot collaboration in the construction sector, a comprehensive review of the scientific literature was conducted. This critical review aimed to identify and synthesize the main research trends in this field. The results of this literature search are presented concisely in Table 5, which summarizes the key findings of the analysed studies, highlighting the state of the art in terms of integrating artificial intelligence, adaptive robotic systems, and immersive technologies in collaborative construction environments.

Table 5: Cutting-edge advances in HRC research for building construction.

Studies	Training in Immersive Virtual Reality for collaborative construction in HRC	Integration of Artificial Intelligence and Robotics for Collaborative Construction	Adaptive Socio-Emotional Systems for Collaborative Robots in Construction
(Gill & Mathur, 2024)		✓	✓
(Obaigbena et al., 2024)	✓	✓	
(Kunz et al., 2022)	✓		
(Reis et al., 2020)		✓	✓
(Wiese et al., 2022)	✓		
(Lim et al., 2024)			✓
(Marcos-Pablos & García-Peñalvo, 2022)		✓	
(Chen et al., 2023)	✓		
(Cano et al., 2023)			✓
(Adami et al., 2022)	✓		
(Zhong et al., 2024)		✓	✓
(S. Liu et al., 2024)		✓	✓
(K. Lin et al., 2020)	✓		✓
(Alenjareghi et al., 2024)	✓	✓	

Based on an exhaustive review of the literature on HRC in the building construction sector, three key developments have been identified in Table 5 that have emerged as spearheads in this field. While these developments offer significant potential to drive the transformation towards Construction 5.0, several studies point to the need for a deeper and more holistic understanding of emerging technologies and their applications in the building sector. There is a consensus around the idea that it is necessary to go beyond the current state of knowledge to fully exploit the opportunities offered by HRC and accelerate the transition towards smarter and more efficient construction (Antonelli et al., 2024; Zafeiris et al., 2018). Accordingly, this study offers an in-depth and critical analysis of the most recent advances in human-robot collaboration and explores its potential application in construction processes, aligned with the principles of Construction 5.0. The importance of optimizing cost-benefit ratios and efficiency, promoting environmental sustainability and regulatory compliance, and fostering adaptability to market dynamics through the implementation of these emerging technologies is emphasized.

4.2.1 Training in Immersive Virtual Reality for collaborative construction in HRC

The successful implementation of HRC in construction is hampered by resistance to change and lack of adequate workforce training. While immersive virtual reality (IVR) offers significant potential to address this issue, its application is limited by the lack of customization, realism and immersion in training environments (Ahmed, 2019). To overcome these limitations, the integration of advanced neurofeedback technologies is proposed. By analysing real-time brain activity through electroencephalography (EEG), it is possible to dynamically adapt IVR training scenarios, adjusting task complexity and interaction with robots based on the learner's cognitive load, attention, and stress (Alimardani & Hiraki, 2020; Stankevich & Sonkin, 2016). This innovative approach allows for optimizing the learning process and maximizing the effectiveness of human-robot collaboration in construction environments. Furthermore, the incorporation of holographic projection technologies, such as ultrasonic levitation and electrostatic tactile feedback, has revolutionized training environments for human-robot collaboration (Rogeau & Rezaei Rad, 2024; S. Wang et al., 2023). These immersive technologies allow users to realistically interact with virtual objects and robots in three dimensions, providing a more authentic training experience. By simulating the physical properties of objects, such as weight, texture, and resistance, intuitive and effective collaboration between humans and machines is fostered. In addition, the advancement of artificial intelligence makes it possible to generate dynamic training scenarios from real-world data, using deep learning algorithms (Baduge et al., 2022; Soori et al., 2023). This combination of holographic and artificial intelligence technologies offers unprecedented potential for training in construction environments, significantly improving the readiness of workers to collaborate with robots on complex tasks (Cha et al., 2020).

Immersive virtual reality (IVR) training environments for human-robot collaboration in construction have been significantly enriched by the integration of multi-sensory technologies. By combining visual, auditory, tactile and olfactory elements, highly realistic and immersive learning experiences are created. Devices such as Head-mounted displays for virtual reality (HMD-VR), spatial audio systems and haptic technologies enable users to interact with simulated construction scenarios intuitively and naturally (Adami et al., 2022; R. Li et al., 2019; Szczurek et al., 2023). In addition, the incorporation of stimuli such as variable lighting, ambient sounds and specific aromas increases immersion and encourages the development of cognitive and decision-making skills adapted to the demands of the work environment (Ohueri et al., 2024; Szczurek et al., 2023). This multi-sensory integration, tailored to the individual needs of each trainee, represents a significant advance in the training of professionals capable of effectively collaborating with robots in the construction sector. Figure 8 presents a visual representation of the progress made in the development of IVR environments designed to facilitate collaboration between humans and robots in the construction field.

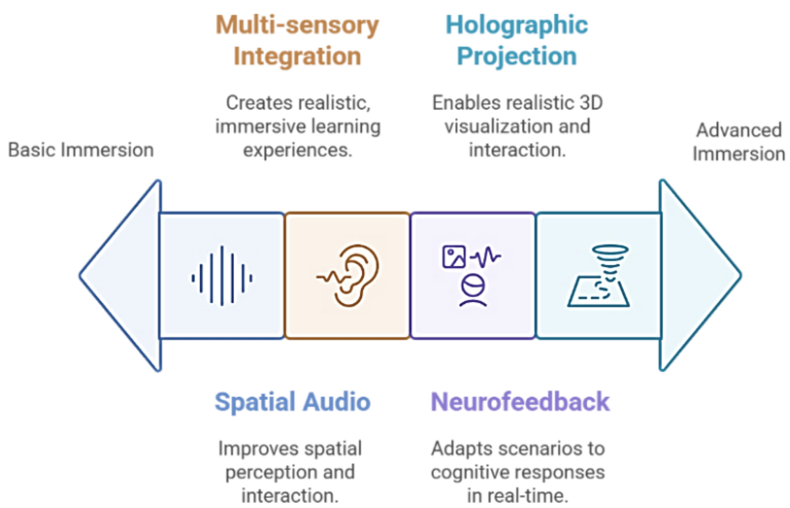


Figure 8: Evolution of IVR training through sensory and interactive technologies.

Advances in IVR have made it possible to realistically simulate construction environments, as illustrated in Figure 8. The integration of brain-computer interfaces, such as neurofeedback technologies, enables real-time adaptation of training scenarios to users' physiological and cognitive responses (Alimardani & Hiraki, 2020; Daeglau et al., 2020). At the same time, the incorporation of haptic and olfactory sensory feedback provides an immersive experience that accurately simulates real working conditions. This combination of technologies optimizes worker training for collaboration with robots in complex construction environments, minimizing risks and maximizing efficiency. Immersive virtual reality (IVR) platforms have evolved significantly thanks to the incorporation of spatial audio technologies, which allow the creation of realistic and immersive acoustic environments (Malik et al., 2020). By simulating the propagation of sound in a three-dimensional space, these platforms improve users' spatial perception and facilitate their interaction with virtual elements, such as robots and tools (Bazzano et al., 2016). On the other hand, the use of artificial intelligence algorithms, based on deep learning, has allowed the development of systems capable of analysing and predicting the behaviour of both humans and robots, thus optimizing the training and decision-making process. Likewise, holographic projection technologies have expanded the possibilities of IVR by allowing the three-dimensional visualization of virtual environments and objects with a high degree of realism. This combination of technologies has given rise to highly immersive and personalized training environments, which facilitate the acquisition of skills and knowledge necessary for effective collaboration between humans and robots in construction environments (Adami et al., 2022; R. Li et al., 2019).

The proposed approach fosters the development of practical skills and spatial reasoning in a simulated environment, which not only optimizes the learning process but also contributes to construction efficiency by reducing material waste and downtime. This methodology, aligned with the principles of Construction 5.0, promotes human-robot collaboration, resource optimization, and the adoption of sustainable practices through virtual simulation and pre-planning.

4.2.2 Integration of Artificial Intelligence and Robotics for Collaborative Construction

Collaborative sorting of materials in construction, powered by AI-powered robots and human interaction, has significant potential to increase efficiency, adaptability and safety in construction environments (Penumuru et al., 2020). However, despite recent advances, there is a lack of research that critically evaluates the implementation of these technologies in construction practice. This line of research proposes an innovative approach that combines neuroscience principles with robot swarm algorithms to address this problem. By equipping these small robots with advanced sensors and communication systems, the aim is to foster fluid collaboration with human workers, thus optimizing the sorting of materials in complex construction environments (Fang et al., 2023). In addition, the possibility of integrating quantum principles into these algorithms is being explored, which could revolutionize the efficiency and accuracy of classification, overcoming the limitations of traditional computational methods (Seo, 2024). This proposal, aligned with the principles of Construction 5.0, aims to significantly reduce waste generation and promote sustainability in the building industry.

The integration of hybrid artificial intelligence systems, combining symbolic reasoning with deep learning, offers a promising solution for accurate material classification in collaborative construction environments (You et al., 2023). This multifaceted approach not only provides human workers with a logical basis for decision-making but also enables robots to perform sorting tasks objectively and reliably, thereby fostering mutual trust between humans and machines (Aggarwal et al., 2022; Soori et al., 2023). Likewise, the incorporation of biometric sensors, capable of measuring physiological variables such as electrodermal activity and heart rate, allows the status of workers to be monitored in real-time, adapting tasks and optimizing human-robot collaboration (Kumar et al., 2021; Xu et al., 2022). This biometric feedback is essential for assessing stress levels, fatigue and cognitive load, contributing to worker safety and well-being. Together, these advanced technologies, as illustrated in Figure 9, are revolutionizing collaboration, paving the way for more efficient, safe and adaptable processes.

Figure 9 presents an overview of the integration of various advanced robotic technologies, including unmanned ground vehicles (UGVs), unmanned aerial vehicles (UAVs), humanoid robots, and specialized construction robots, to establish effective and efficient collaboration with human workers. UGVs can transport heavy materials, level land, and perform repetitive tasks, freeing workers from dangerous and strenuous labour (Patel et al., 2024). UAVs are ideal for inspecting construction sites, creating detailed maps and performing topographic survey tasks, streamlining the planning and monitoring process. (Howard et al., 2018). Humanoid robots can perform tasks that require dexterity and precision, such as panel installation or welding (Kumagai et al., 2019), while specialized robots are designed for specific tasks, such as demolition, painting or bricklaying (Naboni & Paoletti, 2015). Together, these technologies can increase construction productivity, improve building quality, and reduce costs.

These robotic systems are equipped with AI-inspired neural technologies, such as artificial neural networks and spiking neural networks, which give them advanced information processing and decision-making capabilities (Eze et al., 2023; Rajnathsing & Li, 2018; Zafeiris et al., 2018). On this neural foundation, complementary technologies such as quantum principles, deep learning algorithms and biometric sensors are integrated, allowing robots to capture and analyse detailed data on the shape, colour, and texture of materials (Eze et al., 2023; Y. Liu et al., 2021b). This accurate and rapid sorting capability significantly contributes to reducing waste and promoting more sustainable construction practices, aligned with the principles of Construction 5.0.

Figure 9. A1-powered human-robot collaboration in construction.

4.2.3 Adaptive Socio-Emotional Systems for Collaborative Robots in Construction

Despite advances in emotional robotics, its application in the construction field is still in its infancy. However, the ability to recognize and respond to human emotions is essential to foster effective collaboration between humans and robots. Obaigbena et al. (2024) highlight the importance of developing robots with advanced AI capable of interpreting facial expressions and vocal cues, which would allow for providing personalized assistance and improving worker well-being. In the construction context, these robots could act as mediators in conflicts, boost team morale, and even adapt their behaviour based on the emotional state of humans. To ensure positive and efficient interaction, the use of deep reinforcement learning techniques has been proposed (You et al., 2023). While these techniques have been applied in other fields, their potential in construction to foster HRC has not yet been fully exploited. By training robots using deep reinforcement learning, they may be able to adjust their behaviour, maintain a positive attitude, and collaborate more effectively with humans in the execution of construction tasks (Cai et al., 2023; Yu et al., 2021).

A significant advance in HRC is the implementation of brain-computer interfaces to intuitively control robots. This technology allows for more fluid and natural communication between humans and machines, facilitating collaboration on complex tasks such as construction (Y. Liu et al., 2021a). By establishing a direct channel between the human brain and the robot, precise and efficient control is achieved, overcoming the limitations of traditional interfaces (Y. Liu et al., 2021b). In parallel, the integration of real-time emotion recognition algorithms, as proposed by Antonelli et al. (2024) and Mishra et al. (2023), allows robots to interpret workers' emotions, fostering a more harmonious and productive work environment. This emotional adaptability improves safety, well-being, and efficiency in construction projects. Figure 10 illustrates how these advanced technologies can enhance human-robot collaboration, enabling closer and more effective collaboration.

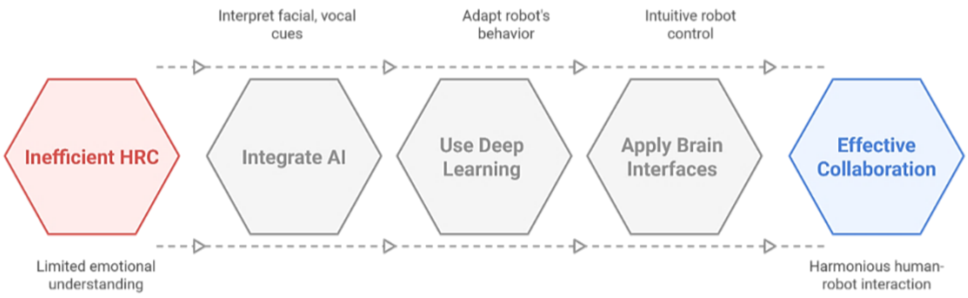


Figure 10: Enhancing construction with emotionally intelligent robots.

Figure 10 illustrates how cutting-edge emotion recognition technologies are transforming human-robot collaboration in the building construction sector. Humanoid robots, equipped with advanced sensors and deep learning algorithms, can interpret human facial expressions and vocal cues with high accuracy. Through the integration of libraries such as OpenCV and Kaldi (Kumaraswamy et al., 2022; Ohueri et al., 2024), these systems can process visual and auditory information, respectively, and determine the emotional state of workers (Kumaraswamy et al., 2022). This ability to recognize emotions allows robots to adapt their behaviour and communication in a more natural and empathetic way, fostering a collaborative and efficient work environment. However, it is important to note that this area of research is constantly evolving, and there are still technical and ethical challenges to be addressed.

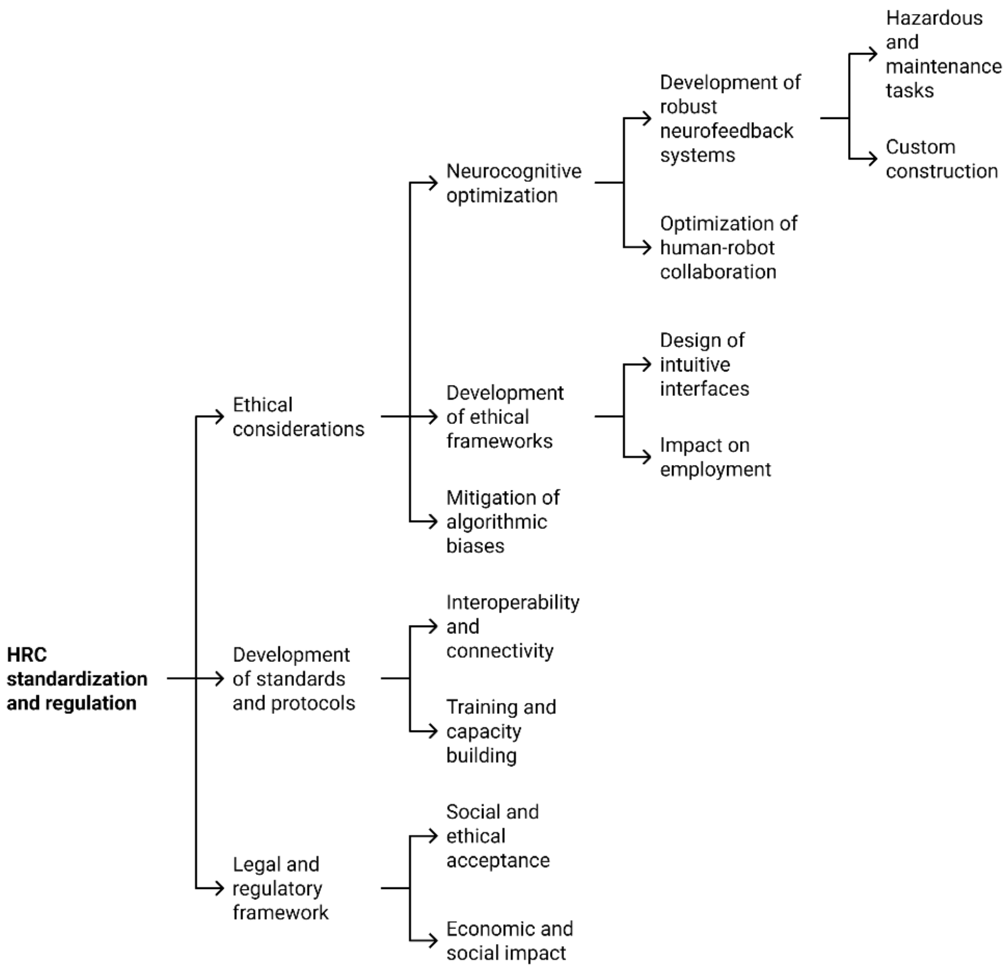


Figure 11: Future Directions and Open Issues for HRC in Construction.

4.3 What are the future directions and open problems for HRC in the building construction process?

This section answers the third research question: What are the future directions and open issues for HRC in the building construction process? Based on a comprehensive literature review, three main research axes have been identified that outline the future of HRC in the building construction sector: neurocognitive optimization of robots for more efficient interaction, consideration of the ethical aspects and algorithmic biases inherent to this technology, and establishment of specific standards and regulations to ensure its safe and effective implementation. These areas of study are crucial to overcoming current barriers and promoting widespread adoption of HRC in the building industry. Each of these research areas will be explored in more detail below.

4.3.1 Ethical Considerations for HRC in Construction 5.0

The implementation of HRC in construction, if accompanied by ethical practices and measures to mitigate algorithmic bias, represents a significant step towards the principles of Construction 5.0. By addressing algorithmic bias, equitable distribution of tasks and more efficient collaboration between humans and robots are promoted, optimizing construction processes (Callari et al., 2024). Ethical considerations also ensure a safe and fair working environment, avoiding over-reliance on technology and prioritizing worker well-being. However, despite advances in research, challenges related to ethics and algorithmic biases in HRC persist, especially in the construction field. The paucity of studies that comprehensively address these issues underlines the urgent need to develop robust ethical frameworks and methodologies to mitigate biases in algorithms used in HRC (Van Wynsberghe et al., 2022), thus ensuring a fair and equitable transition towards building the future.

The absence of a clear roadmap for the ethical implementation of HRC in construction represents a significant obstacle to its development and widespread adoption. This lack prevents effective collaboration between humans and robots, generating legal concerns and resistance from stakeholders (Callari et al., 2024; Ohueri et al., 2024; Van Wynsberghe et al., 2022). It is imperative to develop a robust ethical framework for HRC in construction that prioritizes accountability, equity, transparency, and informed decision-making. It is also critical to establish effective mechanisms to mitigate algorithmic biases, thereby ensuring a balance between technological innovation and societal values. The development of such an ethical framework would not only boost research in the field but also provide practical guidance for the construction industry, paving the way for successful and ethical implementation of HRC in the building sector.

- The lines of research will allow us to advance knowledge about HRC in construction and ensure its development ethically and responsibly, contributing to a more sustainable and equitable future. For example:
- Mitigation of Algorithmic Biases: Development of techniques to identify and quantify biases present in the algorithms used in HRC, and the collection and use of representative data sets to train machine learning models.
- Impact on employment: Study of the effects of automation on employment and the need for just transition policies. Research on the labour implications of HRC, including collective bargaining and worker training.
- Design of intuitive interfaces in different contexts: Development of user interfaces that facilitate the interaction between humans and robots, promoting trust and collaboration. In addition, Research on how to adapt HRC systems to different cultural and social contexts.
- Development of Ethical Frameworks: Definition of specific ethical principles for HRC in construction, considering aspects such as safety, privacy, equity, and responsibility. And the development of methodologies to evaluate the ethical impact of HRC systems throughout their life cycle.

Through a multidisciplinary approach that combines technical, ethical, and social aspects, the potential of HRC in construction can be fully exploited, without compromising human values and principles of social justice.

4.3.2 HRC standardization and regulation in building construction

The absence of specific standards and regulations for human-robot collaboration in building construction represents a significant barrier to the widespread adoption and safe development of these technologies. The lack of standardized protocols can lead to variability in construction processes, increase safety risks, and generate legal uncertainty, which inhibits innovation in the sector. Previous studies have highlighted the urgent need to establish standards and regulations that ensure the interoperability, safety, and reliability of robotic systems and human operators (Hanna et al., 2022; Martinetti et al., 2021). While there are initiatives to develop standards in other areas of technology, HRC in construction still lacks a solid regulatory framework. This regulatory gap limits the potential of HRC and hinders its integration into construction processes (Martinetti et al., 2021).

Successful implementation of HRC in construction requires the development of a robust and agreed regulatory framework covering crucial aspects such as compliance requirements, safety protocols, performance metrics and design specifications (Fosch & Golia, 2019). This regulatory framework will not only ensure the interoperability and safety of robotic systems but will also foster stakeholder confidence and contribute to the actualization of traditional construction objectives, such as cost-effectiveness, efficiency and sustainability (Garcés, 2025).

Future lines of research should focus on developing a robust regulatory framework, assessing social and economic impact, training staff, and identifying successful use cases. By addressing these aspects, a safe and efficient implementation of HRC in construction can be ensured, contributing to the digital transformation of the sector. For example:

- Legal and regulatory framework: The legal implications of implementing HRC in construction need to be analysed and a regulatory framework needs to be developed that covers aspects such as civil liability, data protection and privacy.
- Social and ethical acceptance: The perception of workers, companies and society in general about HRC in construction needs to be investigated, as well as the ethical aspects related to automation and job replacement.
- Development of standards and protocols: Extensive research is required to develop technical standards and safety protocols specific to HRC in construction, considering aspects such as human-robot collaboration, risk assessment, equipment certification and staff training.
- Economic and social impact: The economic and social impact of implementing HRC in construction needs to be assessed, considering aspects such as productivity, job creation, job safety and sustainability.
- Interoperability and connectivity: The development of interoperability standards to enable communication and collaboration between different robotic systems and software platforms, as well as the integration of HRC into construction management systems, needs to be investigated.
- Training and capacity building: Training and capacity building programs need to be developed for workers who interact with robots in the construction environment, ensuring that they have the necessary skills to work safely and efficiently.
- Use cases and applications: Real use cases of HRC in construction should be identified and analysed, evaluating their impact and generating recommendations for their large-scale implementation.

4.3.3 Exploring the potential of neurofeedback-enhanced HRC in building construction

The integration of neurofeedback mechanisms into HRC presents transformative potential for the building construction industry. By optimizing robot performance through neurofeedback, greater efficiency and accuracy in task execution are achieved, resulting in a significant reduction in errors and an increase in construction speed (Daeglau et al., 2020). In addition, the ability of neuro-optimized robots to imitate human cognitive processes facilitates safer and more fluid collaboration with workers, thus reducing occupational risks (Douibi et al., 2021). This combination of efficiency, precision and human-robot collaboration contributes to a more sustainable construction practice by reducing costs, minimizing waste of materials, and allowing a more agile response to unforeseen events (Lemaignan et al., 2017; Mutlu et al., 2016).

Despite the potential of neurofeedback-enhanced HRC in construction, significant gaps in research remain. The lack of detailed studies on collaboration between humans and neuro-optimized robots, as well as the lack of sufficiently robust neurofeedback systems to interpret and respond in real-time to human cognitive states, limit our understanding of the real advantages of this technology. The absence of solid evidence on the safety, cost-effectiveness and efficiency of neuro-optimized robots in construction environments discourages investment and adoption of these solutions (Daeglau et al., 2020; S. Liu et al., 2024; Ohueri et al., 2024). Therefore, further research on HRC with neurofeedback is needed, focusing on identifying and overcoming the challenges associated with the implementation of neuro-optimized robots and the optimization of human-robot collaboration at various stages of the construction process. Future studies should explore how to integrate human cognitive processes into robotic decision-making algorithms, to improve efficiency, safety and sustainability in construction.

The lines of research will allow us to advance knowledge about HRC with neurofeedback in construction and overcome current challenges, opening new opportunities to improve efficiency, safety and sustainability in the sector. For example:

- Optimization of Human-Robot Collaboration: Develop detailed cognitive models of HRC in construction environments to better understand the mental processes involved. In addition to conducting comprehensive security assessments in collaborative work environments to identify and mitigate potential risks.
- Impact on Work Organization: Analyse how the introduction of neuro-optimized robots can modify the organization of work and the tasks assigned to human workers. And develop training and education programs to prepare workers to collaborate with robots and take advantage of new technologies.
- Custom construction: Explore how HRC can contribute to custom construction and digital manufacturing.
- Development of Robust Neurofeedback Systems: Research and develop sensors capable of accurately and in real-time capturing human cognitive states relevant to interaction with robots. And develop robust algorithms to interpret and process neural signals, enabling adaptive, real-time robot responses.
- Hazardous and maintenance tasks: Investigate the use of neuro-optimized robots to perform hazardous or repetitive tasks, improving worker safety, and analyse the ability of neuro-optimized robots to perform maintenance and repair tasks autonomously or semi-autonomously.

Therefore, it is imperative to invest in research to develop theoretical and practical frameworks that can overcome these limitations and fully exploit the potential of HRC with neurofeedback in construction.

5. CONCLUSIONS

The emergence of robotics in construction marks a turning point, positioning robots not as substitutes but as essential collaborators that amplify human capabilities and optimize processes, improving efficiency, productivity, and safety by automating dangerous and repetitive tasks. Despite the growing interest in HRC and Construction 5.0, research that combines both areas to innovate in construction is still in its infancy. To address this gap, this study conducted a comprehensive bibliometric review covering the period 2013–2024, combining bibliometric analysis with a systematic discussion to identify advances and opportunities. Through cluster analysis and the exploration of keyword co-occurrence, co-authorship, and institutional co-affiliation, emerging trends in high-resistance robotics (HRC) applied to construction were discerned, confirming an increase in interdisciplinary scientific production. However, a paucity of specific studies on HRC in buildings was revealed, while key authors and institutions that have consolidated this field of research were identified, in order to contribute to a deeper understanding of the current state and lay the groundwork for future exploration.

Furthermore, the qualitative review further highlighted the research gap, thus corroborating the importance of this study. In addition, recent achievements in HRC in building construction were highlighted. They include: 1) Adaptive Socio-Emotional Systems for Collaborative Robots in Construction; 2) Integration of Artificial Intelligence and robotics for collaborative Construction, and 3) training in immersive virtual reality for collaborative construction in HRC. Furthermore, three future research directions are proposed: 1) ethical considerations for HRC in Construction 5.0; 2) Standardization and regulation of HRC in building construction; and 3) exploring the potential of neurofeedback-enhanced HRC in building construction.

This study provides an up-to-date overview of the advances in human-robot collaboration applied to construction, constituting a valuable reference for the academic and industrial community. By exploring current trends and innovative applications of HRC in the context of Construction 5.0, the research contributes to a better understanding of this evolving field. The findings obtained have significant implications for the training of professionals, the development of training strategies for robots, and the optimization of human-robot collaboration in the construction sector, all aligned with sustainability objectives. It is suggested that future research should focus on further exploring these three areas to advance knowledge and applications of HRC in the construction field.

To maximize the synergy of HRC in construction, it is imperative to complement robotics with disruptive technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT). These tools allow robots to operate with greater autonomy in decision-making, adapt to dynamic environments, and communicate seamlessly with humans and other equipment. The application of virtual and augmented reality, for example, facilitates the visualization and manipulation of 3D models, enabling real-time collaboration between operators and robots. In this scenario, the construction of the future is emerging as a technologically advanced ecosystem where human-robot collaboration, by capitalizing on the inherent strengths of each party, not only accelerates construction processes but also results in safer, more efficient, and highly personalized buildings. The success of this transformation will depend on a gradual and strategic implementation of these innovations, along with adequate workforce training to optimize the use of these emerging tools.

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