Reconceptualising Human-Robot Collaboration in AEC: A PRISMA Scoping Review

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Abstract -

The Architecture, Engineering, and Construction (AEC) industry continues to lag behind other sectors in robotics adoption. A persistent barrier is conceptual ambiguity about what constitutes Human–Robot Collaboration (HRC) in AEC, where definitions often come from manufacturing and do not translate well to dynamic, unstructured work sites. To address this gap, we conducted a PRISMA-guided scoping review of 52 studies, mapping publication trends, geographical distribution, robot types, application domains, interaction and collaboration modalities, and study designs. We show that much of the literature implicitly assumes dyadic, task-centric collaboration and relies heavily on short-term experimental evaluations, often with convenience participants rather than end-users. Based on this synthesis, we propose a construction-specific taxonomy of HRC that foregrounds task flow, temporal coupling, environmental conditions, and the configuration of human and robot roles. We discuss the implications for conceptualising and studying HRC in the AEC, and outline directions for developing more consistent definitions and practice-relevant evidence to support effective robotic adoption.

Keywords -

HRC, AEC, PRISMA, Taxonomy, Robotics Adoption

1 Introduction

The adoption of robotics in the Architecture, Engineering, and Construction (AEC) industry has long been promoted as a means to address challenges related to productivity, labour shortages, and worker safety [1, 2]. While robotic technologies have demonstrated value across construction-related tasks, their uptake in practice remains limited. One promising approach is Human-Robot Collaboration (HRC), which combines robotic capabilities, such as precision, strength, and repeatability, with human adaptability, judgement, and dexterity [3]. Due to this complexity, HRC is often deemed the most advanced application of Human-Robot Interaction (HRI) [3, 4].

Although fully automated construction sites are often presented as a vision of the future, this techno-centric ideal remains constrained by the highly unstructured and dynamic conditions of real-world construction environments [5]. Current robotic systems struggle to operate autonomously under such variability, making human involvement a practical necessity rather than a transitional compromise. In this context, HRC aligns with the broader Industry 5.0 paradigm, which emphasises human-centricity, resilience, and responsible technology integration [6]. By retaining humans in the loop, HRC systems offer a pathway to navigate site complexity while leveraging the complementary strengths of humans and robots.

Despite this potential, the adoption of HRC in AEC remains lagging [4, 2]. A key obstacle is the lack of consensus on what constitutes HRC within the sector. Existing definitions are frequently imported from manufacturing, where workspaces, tasks, and roles are comparatively stable and predictable. As Yu et al. [7] note, these assumptions rarely hold in AEC. As a result, the term HRC is often used to describe a wide range of interaction modalities, from remote tele-operation to physical co-manipulation, without clear conceptual boundaries. For instance, studies grounded in manufacturing standards such as ISO/TS 15066 define HRC as requiring physical co-presence within a shared collaborative space [8, 4], effectively excluding tele-operated systems from the definition. By contrast, other studies explicitly frame tele-operation and shared control as legitimate forms of HRC, treating human oversight of a remotely operating robot as sufficient to constitute collaboration [5]. That the same term is used to describe both physical co-manipulation and remote supervisory control illustrates the field's conceptual instability. This ambiguity complicates cross-study comparison, risk assessment, training design, and the development of standards, ultimately hindering the safe and scalable adoption of HRC in AEC.

To address this issue, this paper presents a PRISMA-based scoping review [9] of HRC research in AEC. Drawing on 52 studies, we systematically map how HRC is defined, implemented, and evaluated in the literature. Based on this synthesis, we propose a construction-specific tax-

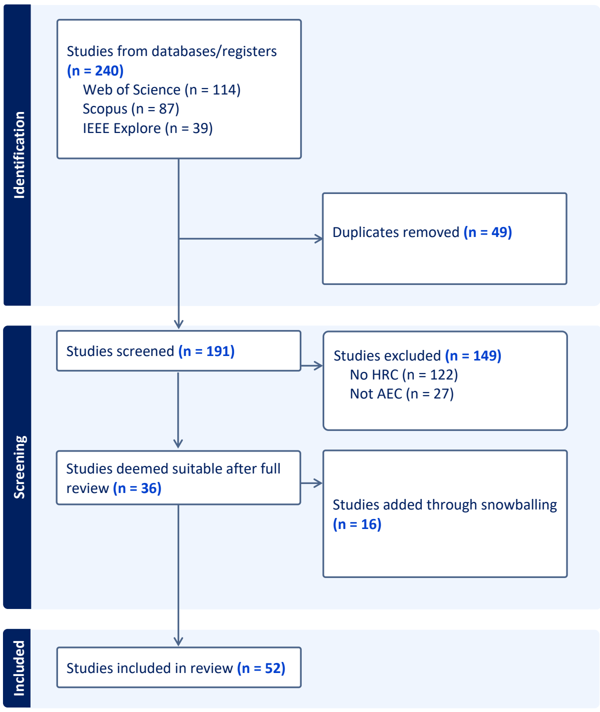

Figure 1. Overview of the inclusion and exclusion process following the PRISMA guidelines.

onomy that captures recurring dimensions through which HRC is conceptualised in AEC research. The paper concludes by discussing implications for future research to support the adoption of HRC in practice.

2 Method

This study conducted a scoping review following PRISMA guidelines [9] to map existing research on HRC in the AEC domain. A scoping review approach was selected because the aim was not to evaluate the effectiveness of particular robotic systems, but to establish the current state of the art and clarify how HRC is conceptualised and studied across the AEC domain.

2.1 Identification

Relevant studies were systematically identified through searches in Web of Science, Scopus, and IEEE Xplore. These databases were selected to capture both AEC-focused outlets and robotics venues, where construction-related HRC research is commonly published. Prior review studies have demonstrated the suitability of Scopus as a primary database for investigating HRC and related human-centred paradigms in construction (e.g., Akhavan et al. [6]). However, given the fast-moving nature of robotics research, where novel systems and interaction paradigms are often first reported in conference proceedings, reliance on a single database risks omitting relevant contributions. Accordingly, IEEE Xplore was included to capture peer-reviewed conference papers from robotics, automation, and human-robot interaction venues that may not yet be indexed in journal-focused databases. Web of Science was included to provide complementary interdisciplinary coverage across AEC research. Together, these databases enabled a broader and more representative capture of recent HRC research in AEC.

The search focused on publications from the last ten years (2016–2026) to reflect the contemporary development of HRC in AEC. Search queries combined terms relating to human-robot collaboration and interaction ("human-robot collaboration", "human-robot interaction", and "human-robot teaming") with terms describing AEC contexts ("AEC", "construction", "architecture", and "pre-fabrication"). To foreground the human-centred dimensions of HRC, additional terms relating to adoption and use were included, such as "adoption", "acceptance", and "human factors". The search term "worker-robot collaboration" was considered but ultimately excluded from the query design, as preliminary searches confirmed that it yielded no additional results beyond those already captured by "human-robot collaboration". Searches were limited to peer-reviewed journal articles and conference papers published in English.

2.2 Screening and eligibility

Records were screened in two stages. First, titles and abstracts were reviewed to exclude studies clearly outside the scope of this review. Studies were excluded at this stage if they did not involve humans working with robotic systems or addressed robotics in contexts other than AEC, such as manufacturing settings. Studies focusing on robotic fabrication without human involvement were also excluded.

Second, full-text screening was conducted to assess eligibility in greater detail. Three authors reviewed the full texts of the remaining studies and discussed inclusion decisions. Studies were included if they investigated HRC within AEC contexts, including construction, architecture, pre-fabrication, or related built environment applications, and explicitly examined interactions between human workers and robotic systems.

To ensure comprehensive coverage of influential and emerging work, snowballing were conducted on the reference lists of included studies. This process also drew on proceedings from prominent architecture and construction conferences, including ISARC and ACADIA, where relevant HRC research is emerging. Through this snowballing process, an additional 16 studies were identified and included. In total, 52 studies formed the final dataset for analysis. Figure 1 summarises this process.

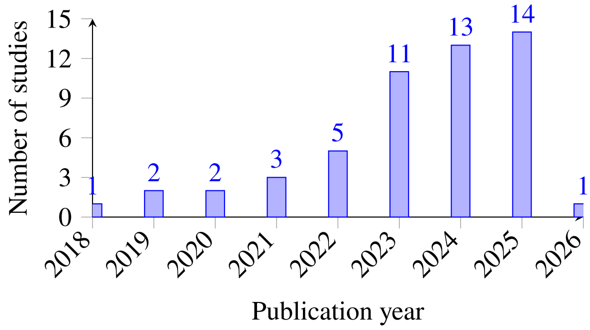

Figure 2. Included studies by publication year.

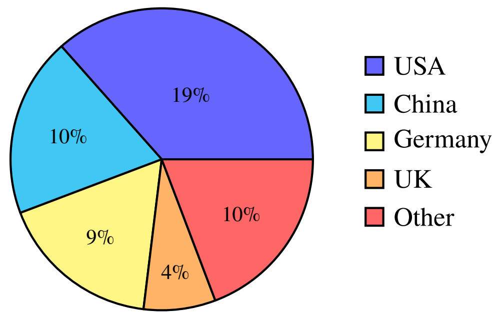

Figure 3. Study distribution by country.

2.3 Data extraction and synthesis

For each included study, descriptive information was extracted, including publication year, geographical location, robot type, application domain, study type, and the reported HRC form. Rather than applying predefined categories of collaboration, the analysis focused on how HRC was described and used within each study. An inductive synthesis was then conducted to identify recurring patterns, inconsistencies, and gaps across the literature. The synthesis was carried out by the research team, drawing on iterative discussion and comparison across studies. These insights informed the development of a context-specific taxonomy of HRC tailored to the AEC domain. The taxonomy was developed inductively from the review findings, with candidate dimensions identified, compared, and refined through iterative discussion among the research team. Alternative dimensions were considered and consolidated where overlap was identified. The research team's combined expertise, spanning 40+ years in AEC and 10+ years in HRC research, informed the analytical judgements made throughout this process.

3 Results

This section presents a descriptive overview of the 52 studies included in the scoping review. The results characterise publication trends over time, geographical distribution, robot types and application domains, interaction modalities, and study types and evaluation approaches.

3.1 Publication trends over time

The 52 studies included in the review were published between 2018 and 2026, with an increase in publication activity over time (Figure 2). Early work was limited in volume, with one study published in 2018, followed by a small number of publications between 2019 and 2021 (e.g., [10, 11]). Publication output noticeably increased from 2022 onwards, reflecting growing research interest in HRC within AEC contexts (e.g., [12, 13]). The majority of studies were published in the latter half of the review period. Eleven studies appeared in 2023, followed by 13 in 2024 and 14 in 2025. A small number of studies published in 2026 were also captured, reflecting the inclusion of early-access journal articles and conference papers.

Across the review period, conference papers accounted for a substantial share of the literature (N = 31 of 52 studies). This pattern reflects the fast-paced, exploratory nature of HRC research in AEC, where novel systems and interaction paradigms are frequently reported for the first time at conferences (e.g., [8, 14, 15]). In contrast, journal publications (N = 21 of 52 studies) became increasingly prominent in later years, suggesting a gradual consolidation and maturation of the research field (e.g., [16, 17]).

3.2 Geographical distribution of studies

The geographical distribution of the included studies shows a concentration of HRC research in a limited number of countries, alongside broader international participation (Figure 3). The USA contributed the largest share of publications, followed by China and Germany. These countries host several major research groups and initiatives focused on construction robotics and human-centred automation (e.g., [1, 18, 16]). A smaller number of studies originated from the UK. In contrast, the remaining studies were distributed across countries, including Korea, Spain, South Africa, Austria, Australia, France, Iran, and Canada. Collectively, these contributions indicate that HRC research in AEC spans multiple regions worldwide, although the distribution remains uneven.

3.3 Robot types and application domains

The 52 studies investigated a diverse range of robotic platforms used for HRC within AEC contexts. Each study was categorised according to its primary robot platform, reflecting the main system under investigation rather than all robots mentioned. Studies whose primary contribution was conceptual, methodological, or perceptual were retained in the review but not included in robot-type counts.

Industrial robotic arms, including collaborative robot arms, were the most commonly studied platforms. These systems were typically deployed in controlled or semi-controlled environments, such as prefabrication facilities and fabrication laboratories, with application domains including timber assembly, masonry construction, material handling, and assisted fabrication (e.g., [8, 16]). Several studies examined robotic arms mounted on mobile bases, enabling limited on-site mobility while maintaining structured task execution ([14]).

Wearable robots constituted another category, primarily in the form of exoskeletons and robotic limbs. These systems were designed to augment human physical capability rather than replace human labour, with applications focused on lifting assistance, overhead work, and ergonomic load reduction (e.g., [19, 20]). Studies in this category frequently examined physical strain, usability, and worker perceptions in both laboratory and field settings.

A smaller number of studies investigated task-specific construction robots developed for particular operations, such as bricklaying, sealant application, drilling, fastening, and inspection (e.g., [21, 22]). These robots were often purpose-built; evaluated in experimental or pilot contexts.

Tele-operated and human-in-the-loop HRC systems were also represented. In these studies, robots were controlled directly by human operators or trained using techniques such as learning from demonstration, with applications including performing hazardous operations (e.g., [23]). Across robot types, fully autonomous operation was rare, with robots consistently positioned as collaborative partners supporting human work.

3.4 Interaction and collaboration modalities

HRC was operationalised through a range of collaboration modalities. Tele-operation (remote control) were common, particularly in studies addressing hazardous tasks (e.g., [21]). In these cases, collaboration was framed as human-in-the-loop control, with robots acting as extensions of human capability.

Shared control and supervisory interaction models were also prevalent, distributing control authority between the human and robot, either temporally or functionally (e.g., [24, 23]). These arrangements were frequently adopted to balance safety, flexibility, and task performance in unstructured construction environments.

Several studies examined co-located collaboration, in which humans and robots operated in the same physical workspace. These interactions included sequential task execution, handovers, and coordinated work within shared spatial boundaries (e.g., [11]). Physical co-manipulation, both the human and robot manipulating the same object simultaneously, was less common but appeared in assembly and prefabrication contexts.

Wearable robotic systems introduced an embodied form of collaboration, with continuous physical coupling between human and robot ([19]). Across modalities, humans retained decision-making authority, while robots supported or executed specific aspects of work.

Across studies, collaboration was mediated through enabling technologies such as augmented reality, virtual reality, and digital visualisation systems (e.g., [25]). These technologies supported task guidance, training, and shared situational awareness, and were often integral to coordinating action under dynamic site conditions.

3.5 Study types and evaluation approaches

The included studies employed a range of study designs and evaluation approaches. Experimental laboratory studies were common, particularly for research conducted on robotic arms, wearable robots, and interaction techniques under controlled conditions (e.g., [11, 12, 16]).

Field-based and in-situ studies were less frequent but provided insights into how HRC occurs in real or semi-real construction environments (e.g., [19, 20]). Prototype demonstrations and proof-of-concept studies presented novel robotic systems or interaction frameworks, often evaluated through limited user testing (e.g., [8, 14, 15]). Several studies relied on participants who were not representative of the intended end-users in construction settings.

Across the reviewed studies, quantitative evaluation approaches predominated, with a strong emphasis on controlled experiments, usability testing, performance metrics, and questionnaire-based measures (e.g., [16, 17]). In contrast, qualitative methods aimed at understanding workers' situated practices and needs in real construction environments, such as in-situ observation, interviews, or longitudinal field engagement, were comparatively rare and typically limited in scope (e.g., [19, 20]). As a result, much of the existing evidence foregrounds system performance and user responses under experimental conditions, rather than the contextual realities of construction work.

3.6 A construction-specific taxonomy of HRC

Synthesising patterns across the reviewed studies, we propose a construction-specific taxonomy of HRC that captures how collaboration is organised and enacted on construction sites (Table 1). Rather than classifying systems by robot type or level of autonomy, the taxonomy foregrounds structural properties of collaboration that recur across application domains, including task flow, temporal coupling, environmental conditions, and the configuration of human and robot roles. These dimensions reflect how HRC occurs in dynamic, unstructured, and safety-critical construction environments, and provide a conceptual lens for comparing collaborative arrangements across otherwise heterogeneous systems.

Table 1. A construction-specific taxonomy of HRC in on-site contexts.

HRC Task	Drone-based site surveying & inspection	Tele-operated / mobile on-site robotic assistance	Robotic bricklaying with human coordination	Wearable robots & exoskeleton-assisted work
Task flow	Asynchronous; loosely sequenced HRC	Predominantly synchronous; real-time human intervention possible	Mixed sequential and synchronous task execution	Fully synchronous; continuous real-time coupling
Temporal coupling	Low	Moderate	Moderate to high	High
Environment	Unstructured outdoor site; evolving terrain and layout; spatially separated HRC	Unstructured, safety-critical on-site conditions; confined or hazardous areas; partially shared or remotely mediated space	Shared on-site workspace; dynamic layout; multiple concurrent trades	Unstructured, physically demanding on-site environments; fully shared and embodied space
Human role configuration	Operator, surveyor, engineer, site manager; roles distributed and loosely coupled	Primary operator with safety spotters and supervisors; roles shift during execution	Skilled workers and supervisors; roles fluid and task-dependent	Single primary wearer with supervisory and safety oversight
Robot role configuration	Sensing and data acquisition tool supporting downstream human decision-making	Executor or assistant under human oversight; role shifts with control mode	Task executor for repetitive or precision placement within human-coordinated workflow	Embodied assistant augmenting human physical capability
Personalisation and adaptation	Limited; workflow-level adaptation; learning primarily on the human side	Moderate; interface and control tuning to operator skill and experience	Low system-level adaptation; human teams adapt practices over time	High potential; assistance tuned to individual users, bodies, and tasks

4 Discussion

This review sought to clarify how HRC is conceptualised and studied within AEC and to identify directions for advancing both research and practice. The results highlight a growing, increasingly diverse body of work but also reveal persistent conceptual and methodological limitations that constrain how HRC is understood in AEC.

4.1 Reconsidering HRC beyond dyadic definitions

Most established definitions of HRC originate from manufacturing contexts [4, 26], where collaboration is framed as a dyadic relationship between a single human operator and a single robot working in close proximity, implicitly assuming stable roles, clearly bounded workspaces, and limited environmental variability. This framing does not translate well to construction sites, which are characterised by dynamic conditions, evolving tasks, and heterogeneous teams. Several studies implicitly challenged this boundary by treating tele-operation as a valid form of HRC. For instance, Rasines et al. [21] framed human involvement through remote control as constitutive of collaboration rather than a precursor to it, yet such a system would fall outside HRC entirely under standards such as ISO/TS 15066 [8, 4]. Across the reviewed studies, collaboration frequently unfolded within teams, with multiple workers interacting with, supervising, or coordinating around a robotic system (e.g., [11, 16, 19]). Roles were fluid rather than fixed, and responsibility shifted dynamically in response to task demands and robotic limitations. Yang et al. [27] illustrate this well: in a timber assembly study, assembler and installer roles shifted when robotic errors occurred, requiring workers to negotiate intervention strategies and temporarily assume control. These observations confirm that a dyadic understanding of HRC is insufficient for construction practice.

Enabling technologies further complicate dyadic definitions. Unlike manufacturing, where collaboration is often achieved through direct spatial coupling, many AEC systems rely on augmented reality, tele-operation interfaces, or BIM-linked visualisations to coordinate work, support decision-making, and manage risk (e.g., [28, 29]). These technologies shape how roles are negotiated, authority is exercised, and collaboration is sustained over time on dynamic sites.

HRC in AEC should therefore be conceptualised as a system-level phenomenon. From this perspective, a construction site can be understood as a socio-technical HRC system in which humans and robots work toward shared goals, with collaboration occurring wherever human and robotic contributions are temporally coupled and mutually interdependent [30]. This framing accommodates multiple human actors with evolving roles and shared decision-making authority [27], while preserving dyadic definitions for comparatively structured fabrication and prefabrication environments [15, 4]. The contribution is therefore not a universal redefinition of HRC, but a construction-site-specific conceptualisation that reflects the realities of AEC environments.

4.2 Methodological implications for studying HRC in construction

The review highlights a strong methodological skew toward quantitative and experimental research approaches.

Many studies relied on controlled laboratory experiments, usability testing, and short-term performance measures, often conducted with convenience participants such as university students (e.g., [12, 16, 17]). While such approaches are valuable for early-stage system development and controlled comparison, they provide limited insight into how HRC is experienced, learned, and sustained in real construction settings. Experimental evaluations typically neglect the complex conditions under which construction work is performed, including environmental variability, organisational constraints, and the presence of multiple interacting actors. Field-based and qualitative investigations remain comparatively rare, but offer important insights into how HRC unfolds in practice (e.g., [22]). These approaches are particularly well-suited to capturing workers' situated practices, evolving roles, and the organisational contexts that shape collaboration on construction sites.

4.3 Directions for future research

The findings of this review point to several priorities for future research on HRC in AEC. First, there is a need to move beyond dyadic, task-centric models of collaboration and to systematically investigate team-based HRC involving multiple human actors. This research priority includes examining how different roles emerge, how leadership is shared or transferred, and how coordination is achieved under dynamic site conditions. Understanding these processes is essential for designing HRC systems that can operate within the complex social and organisational realities of construction work. Second, future studies should place greater emphasis on real-world deployment and sustained use. Understanding HRC as it unfolds in practice requires engaging with end-users in their actual work environments [3, 31] and recognising that collaboration is shaped by experience, learning, and context. Third, future work should empirically test and explore emerging collaborative configurations that extend beyond the scenarios captured in the present review, including multi-robot collaboration and AI-mediated task allocation. We anticipate that no single robot will address the full range of challenges present on a construction site; rather, we envision a future in which multiple robots of different types operate in concert with human teams, making it essential to develop taxonomic frameworks capable of accommodating such heterogeneous arrangements. Additionally, a dedicated review of enabling technologies such as augmented reality, digital twins, and tele-operation interfaces, and how they mediate collaboration dynamics in AEC, would constitute a valuable contribution to the field.

Finally, advancing HRC in AEC will require methodological pluralism. Quantitative measures of performance and usability should be complemented by qualitative insights into workers' lived experiences, concerns, and strategies. Such an approach is essential for developing collaborative robotic systems that are not only technically functional, but also socially and organisationally viable within the complex realities of construction work. For instance, introducing humanoid workers who can record performance metrics might not pair well with workers' perceived fear of surveillance [8], therefore limiting acceptance and constraining adoption.

5 Conclusion

This paper presented a PRISMA-guided scoping review of Human–Robot Collaboration (HRC) in the Architecture, Engineering, and Construction (AEC) domain, synthesising 52 studies from the last decade. The results reveal rapid growth in recent years alongside two challenges: HRC is frequently framed using dyadic, manufacturing-derived definitions that do not reflect the dynamic, team-based realities of construction sites; and the evidence base remains skewed toward short-term experimental evaluations with convenience participants. In response, we proposed a construction-site-specific conceptualisation of HRC as a socio-technical system, accommodating multiple human actors, evolving roles, and temporally coupled collaboration. Future research should prioritise in-the-wild and qualitative or mixed-methods studies, with particular attention to team HRC, role negotiation, and dynamic leadership, to build the practice-relevant evidence needed for safe and scalable HRC adoption in AEC.

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