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ORIGINAL PAPER

Sociotechnical considerations on developing human robot teaming solutions for construction: a case study

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Abstract

This research advocates for a paradigm shift in the exploration of human–robot teaming solutions for construction automation, by focusing on an integrated view of sociotechnical systems (STS) that recognize the inter-dependencies among actors at various levels when tracing how innovative ideas about intelligent robotic technologies translate into practice in the construction sector. Through a qualitative case study, the paper examines industry and organizational considerations for developing and adopting robotic technologies, leadership vision, mediation, and change management to propose integrative strategies to enhance expectations, acceptance, and deployment of intelligent technologies in human–robot teams (HRTs). This study contributes to research in construction robotics at three organizational levels—macro, meso, and micro. The Integrated Human–Robot Teaming Framework and associated workplan schema offer guidance for navigating human–robot teaming complexities. The study recommends adopting STS principles in planning and deploying robotics applications for construction, emphasizing the integration of multiple elements across the lifecycle. Active leadership and mediation emerge as critical elements in navigating complex networks, ensuring successful outcomes in the dynamic construction environment.

Keywords Sociotechnical systems · Intelligent robots · Construction automation · Organizational change

1 Introduction

The Australian construction industry contributes to 10.8% of the nation's gross domestic product (GDP), and employs 1.35 million people (MBA 2023). While it is set for growth (NSC 2022), the industry suffers from a range of issues including poor workplace health and safety; repetitive labor-intensive work resulting in boredom and absenteeism; dangerous or hazardous physical situations; material wastage and severe shortage of skilled workers that has been further exacerbated by border closures during COVID-19 Pandemic. These challenges are not unique to Australia but are also faced by the construction sector internationally.

The need for construction robots re-emerged after 2015 (Chang et al. 2022) as a result of Governments such as Hong Kong encouraging the construction industry to adopt emerging technologies. More recently, robotic solutions have started contributing to address some key issues faced by the construction sector through improved labor conditions, worker safety, productivity, and quality (Bock and Yoshida 2016). These robotic solutions are designed to automate tasks in complex unstructured outdoor environments and under hazardous conditions (Bock and Yoshida 2016). While autonomous industrial robots can be applied in the manufacturing sector where they carry out tasks from a safe location, the construction environment is dynamic and could pose obstacles to such robots moving by themselves to carry out tasks. Therefore, collaborative robots would be more applicable in the construction sector to work inter-actively and collaboratively with humans in close proximity, allowing human sense perception and complex decision-making abilities to be combined with robotic power and endurance (Wang et al. 2022). However, the socialization of intelligent robotic technologies with a human workforce, roles, and the

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technical capacity of the workforce to organize, design, program, operate, and work with robotic technologies is still an emerging field in the construction sector (Han et al. 2021; Liang et al. 2021).

Researchers have previously identified a need for task-specific technologies grounded in fundamental principles and properly scaled. They proposed that emerging technologies will benefit from increased inter-disciplinary research and emphasize the importance of training to address skilled labor shortages and maximize advancements in automation (Melenbrink et al. 2020). We posit that to successfully integrate robotic solutions in the construction sector, it is crucial to adopt a holistic approach that considers both technical advancements and the social dynamics of human–robot collaboration, particularly as a team. A human–robot team (HRT) can be broadly defined as a collaborative effort where people and robots work together on a task, sharing the same workspace and interacting with the same objects (Hoffman and Breazeal 2004). Acknowledging the interconnectedness of these aspects will ensure that the technology is both effective and widely accepted by the workforce. When automation is introduced into industry where technology and people have to interact, sociotechnical systems theory has been applied to deal with challenges of acceptance and adoption that could support implementing organizational change in the way work is carried out by humans who were previously used to working on the tasks manually (Emery and Trist 1972; Pasmore et al. 2019).

To highlight the importance of sociotechnical systems (STS) design, we use a case study about the design and implementation of an intelligent robotics solution in the Australian construction sector. From the literature reviewed for this paper, we found that sociotechnical systems thinking and organizational change to adopt human–robot teaming solutions were rarely addressed in journal publications about automation in construction.

This paper addresses a significant gap in the literature by identifying key themes about the development and deployment of Human–Robot Teams (HRTs), focusing on the complex sociotechnical factors at multiple system levels in the construction sector. It proposes an Integrated Human–Robot Teaming Framework and associated workplan schema that emphasize a holistic approach, offering guidance at the macro, meso- and micro-system levels. The framework and schema facilitate the process from strategic vision and ideation through design and development to implementation or deployment on-site, ensuring that technical and social aspects are integrally considered throughout the process lifecycle.

This paper is organized as follows. In Sect. 2, we present a review of the extant literature to outline human–robot considerations, particularly the use of robot technologies in construction from an STS perspective. Section 3 details the research design and methodology. Section 4 covers data collection and analysis. Section 5 presents the findings. In Sect. 6, we discuss the thematic categories including its system-wide fit at different hierarchical work levels, workplans, and the implications. The research limitations and future research is discussed in Sect. 7. Finally, Sect. 8 summarizes and offers the conclusions from our exploration.

2 Brief literature review

The literature reviewed covers robot technologies in construction and organizational and social factors in adopting automation solutions in organizations in the construction sector.

2.1 Robot technologies and construction

There is an increasing demand for robots that can interact and cooperate with people in human environments, sharing physical space, and working closely with humans in joint tasks (Cunha et al. 2020). Collaborative robots do not operate from cages but are in direct contact or a shared space with the operator. Operators and robots as a human–robot team tend to perform selected tasks jointly. Based on Knudsen and Kaivo-Oja (2020), the distinction between collaborative robots and traditional industrial robots is the direct interaction with human workers. In theory, organizations can "leverage the strengths and endurance of robots with the tacit knowledge and agile decision-making skills of humans" (Knudsen and Kaivo-Oja 2020, p. 14).

The need for construction robots has seen rapid growth in the industry after 2015. Carra et al. (2018, p. 1) reported that the 'robotics community has demonstrated a growing interest toward application in the construction industry in the last 15–20 years. Their review of applying robotics in construction showed case studies of application in demolition in the US and tunnel inspection in Spain. Bock (2015) explained that following the introduction of robots in manufacturing and ship building, robots began to appear on building sites in the 1980s. His review of such robots included several examples of robots used in construction in Japan. Bock (2015) suggested that 'using robotic technologies in prefabrication, onsite construction, and services' (p.122), the industry can provide building products economically, enhance quality of products and provide humane work conditions for the workers. Subsequently, evolution pathways for robotics technologies in construction sites showed examples of brickwork robots, large-scale three-dimensional printing robots, and facade construction robots. A range of other new robotics technologies found within the construction sector include vision systems for safety, 3D printing of materials, the use of drones for inspection, augmented reality in training, and autonomous systems for earthmoving and materials handling (Melenbrink et al. 2020; Müller et al. 2020; Robotics-Australia-Group 2022). Despite the growth of robotics technologies and efforts to develop automation solutions, examples like Katerra in USA demonstrate significant organizational challenges when integrating social and technical aspects. Katerra's mission to integrate and streamline construction saw itself struggling with material quality, stakeholder and governance issues, and market readiness, leading to the closure of its Phoenix factory (Brenzel and Jeans 2019). Additionally, Katerra's lack of involvement from the design inception of projects exacerbated these issues.

On the other hand, Shimizu successfully developed systems that could be used directly on construction sites, rather than just in factory environments (Bock 2015). These included single-task construction robots which performed specific tasks repetitively. However, their lack of integration with other construction processes and the need for safety measures limited productivity gains. Shimizu has been developing concepts for integrated automated sites. Over time, robot systems advanced to operate effectively in unstructured environments similar to those where humans work (Bock 2015).

In Australia, Aurecon has introduced robotics technology into construction in collaboration with major partners Murdoch University and University of Technology Sydney (Aurecon 2022). Laing O'Rourke has invested in fully autonomous vehicles, artificial intelligence, and a start-up for advanced sensing and perception system (Robotics-Australia-Group 2022). Collaborations between MPC Kinetic and Built Robotics saw the deployment of robotic excavators that improved productivity by allowing skilled excavator operators to focus on higher complexity tasks, resulting in the creation of a new class of worker—Robotic Equipment Operators (Robotics-Australia-Group 2022). Australia-based Fastbrick Robotics developed Hadrian X, initially targeting the residential market but shifting to a "Wall-as-a-Service" model due to limited interest (FBR 2023). In contrast, US-based Construction Robotics introduced the MULE (Material Unit Lift Enhancer), a lift-assist robotic arm designed to aid rather than replace human masons (Construction-Robotics 2024). While Hadrian X excels in specific wall-building tasks, MULE's flexibility, and alignment with the conventional practices give it a stronger market foothold.

This brief review of robot technologies in construction demonstrates the transformative potential of robot technologies in the construction sector, supported by a resurgence in demand post-2015. Historical perspectives and international case studies outline many of the applications of these robotics technologies; however, it is not always necessary that the technologies are successful in practice from the onset. While frameworks for integrating robotics exist, there remains a gap in understanding the practical implications and social considerations of translating and integrating intelligent robot technologies into applicable solutions for the construction sector involving human–robot collaborations through human–robot teams. This gap sets the stage for the first research question (RQ) that bridges the current knowledge gap and guides future developments in the field:

RQ1 "*How do innovative ideas about intelligent robot technologies translate into practice in the construction sector?"*.

2.2 Organization, technical and human social considerations

Construction activities comprise fundamentally inter-disciplinary and intertwined tasks requiring the consideration of business, technical, and human–social perspectives, with workers and the community representing significant constituencies (Robotics-Australia-Group 2022). Organizations expect solutions with clear advantages to the core business before investing in innovative technologies. Riskiness, impacts on roles, task outcomes, and operational realities can result in barriers to adoption of robot technologies by the organization (Robotics-Australia-Group 2022). Additionally, a solution's acceptance into the work environment could be low if workers feel unsafe, threatened, or unable to see the benefits of working alongside an intelligent robot (Delgado et al. 2019) giving rise to social acceptance.

Beyond showcasing technological advancements in robotics, studies showed that although automation can reduce perceived workloads, it can also increase cognitive load in monitoring tasks (Stapel et al. 2019). Frazier et al. (2022, 2024) and Karakikes and Nathanael (2023) focused on cognitive workload in automated environments. Additionally, Jipp (2016) explored how different types of automation impact skill development, showing that decision automation can accelerate expertise development by stimulating reasoning, whereas information automation may increase reliance on working memory. This differentiation demonstrates the criticality of designing automation that supports skill development and cognitive capacities. Moreover, the literature also addressed the evolving skill requirements due to automation. For instance, McKinsey Global Institute (2018) and Parker and Grote (2022) emphasized the need for education and training to help workers adapt to technological changes. McKinsey highlighted the increasing demand for technological, social, and higher cognitive skills, whereas Parker & Grote stressed the importance of proactive work design and educating a broad range of stakeholders about job crafting and work design principles.

These studies highlighted the nuanced impacts of automation on cognitive demands and decision-making authority, suggesting the need for careful systems and role design, skills, and capacity development that allow for adaptability to manage changing cognitive loads and optimize performance in human–robot teams (HRT).

Based on task complexity and automation levels, Christiernin (2017) categorized different levels of HRCs ranging from no collaboration to full collaboration in human–robot interactions. The model could be useful as a basis for discussions between robot manufacturers, automation consultants, and industrial partners to define requirements and select appropriate robotic solutions. However, the paper did not fully consider the adaptatability and joint optimization between humans and robots as an integrated team working together in a dynamic, unstructured environment such as construction sites.

Stakeholder perceptions and ethical considerations are critical in the deployment of robotic technologies. Kim et al. (2022) revealed diverse views among construction professionals based on safety risks, dexterity requirements, and complexity of tasks. The authors emphasized the importance of aligning robotic roles with stakeholder needs and job characteristics to ensure successful integration. Meanwhile Liang et al. (2024) addressed the ethical implications of AI and robotics, such as job displacement fears, data privacy, transparency, trust, and liability. These concerns require proactive management to ensure responsible implementation and workforce acceptance of new technologies.

Pan et al. (2018) employed a combination of qualitative and quantitative research methods, including industry surveys, case studies, co-creation workshops, and a pilot project resulting in proposing a methodological framework for integrating robotics into construction. They highlighted practical challenges, such as the need for standardized protocols, comprehensive training, and supportive regulatory frameworks. Their emphasis on co-creation of robotic solutions through stakeholder engagement aligns closely with the STS approach.

The STS approach emphasizes the holistic integration of social and technical subsystems to enhance system performance and worker well-being. This approach is critical in understanding the integration of robotics in construction, where collaborations between humans and robots must be carefully designed to account for both human and technological factors. Therefore, designers of robotics solutions should consider STS design principles. This may require them to follow an iterative and participative approach to solutions development with regular inputs from stakeholders who will buy into adopting solutions developed for them. In support of these design requirements, Norman and Stappers (2015) suggested that designers such as those in robot technologies should play an active role in implementation, and develop solutions through small, incremental steps—to reduce political, social, and cultural disruptions. This could result in moving away from treating a robot as simply a product but as a solution developed in collaboration with its users. This would require a change in the design approach from a goods or product-dominated logic to a service-dominant or value-dominant logic (Barnett et al. 2014; Lusch and Vargo 2014).

Moving away from a product-dominant logic implies that innovative organizations need to have to shift their mindsets from developing products on their own for the market to co-creation of solutions with users and their various stakeholders. Collaborative endeavors in robot technologies for construction projects need to be flexible and adaptable as there are often many uncertainties and emergent elements to deal with (Schneckenberg et al. 2017).

With the burgeoning awareness of human systems integration, human-centered design methods, and design thinking, design engineers no longer work in isolation but have started to work in complex sociotechnical arenas (Norman and Stappers 2015). As robots need to deal with human (or social) and technological aspects simultaneously, they can be identified as a complex system (Brocal et al. 2021) with a sociotechnical function (Kant 2016). Robots might perform well in repetitive and monotonous tasks, but human workers handle unexpected and unplanned tasks better, implying that humans are still the more flexible resource in a system where robots and humans work together. STS studies need to consider the interactions between robots and humans, integrating the technical and cyber factors of the interactions with the organizational, physical, and mental dimensions, whereby workers are active players rather than spectators in the collaboration (Kant 2016; Peruzzini et al. 2020).

Pan and Pan (2020) acknowledged the lack of studies in stakeholder perceptions to help elaborate development requirements and dialectics of construction robots. The literature often treats stakeholders as homogeneous groups or focuses on specific perspectives (e.g., workers or managers). There is a need for comprehensive studies that map the roles and interactions of various stakeholders (e.g., designers, engineers, managers, workers, and consultants) throughout the lifecycle of robotic technology implementation. This includes exploring how these roles might evolve and how stakeholder collaboration can be optimized to support successful integration.

The review exploring organization, technical and human social considerations highlights the complex and multifaceted nature of emerging robotic technologies in the construction sector, specifically in the development and integration of human–robot teaming solutions. The identified gap lies in the need for an in-depth understanding of the roles played by various stakeholders from ideation to deployment. Stakeholders, including human workers and the user community, are highlighted as significant constituencies, and the reluctance to adopt robot technologies is attributed to concerns about riskiness, impacts on roles, task outcomes, and operational realities.

The unique challenges and requirements of construction work necessitates the need for a shift in mindset toward co-creation of solutions with users and stakeholders, particularly in the context of construction robotics and human robot teams.

This brings us to ask the second and third research questions to be addressed in this paper:

RQ 2—*What roles do various stakeholders play from ideation to deployment in innovation projects providing human–robot teaming solutions to the construction sector?*

RQ 3—*How might human–robot teaming be characterized and operationalized in the construction sector?*

This paper adopts an STS as a theoretical framework to address the research questions that are discussed next.

2.3 The sociotechnical systems (STS) perspective

By definition, STS are heterogeneous, that is, they comprise components with different characteristics at different levels of application and adoption. Design in such complex settings is not limited to single persons, phases, or solutions (Norman and Stappers 2015). Therefore, designers, systems engineers, workers, and management have a role to play in a sociotechnical system. This perspective of STS heterogeneity has led to a stream of studies in human-centered design and participatory design (Hussain et al. 2012; Nasadowski 2015) in the STS body of literature.

Sociotechnical systems theory explores how the introduction of new technology in organizations impacts on people and specifically how multi-skilled people work together as self-organized units to optimize social and technical systems (Emery and Trist 1972). At its core, STS advocates that the design and performance of any organizational system can only be understood and improved if both ‘social’ and ‘technical’ aspects are integrated and considered as interdependent parts of a complex system that includes the people, technology, infrastructure, culture, processes or procedures, goals, and metrics or measures. In essence, optimal performance in such systems requires attendance to both the social and technical aspects of work organization (Emery and Trist 1972).

STSs reside in complex, chaotic, self-organizing emergent systems. Contemporary STS studies emphasize the complex horizontal and vertical inter-relations and inter-dependencies among activities, workgroups, and tasks including their subtasks. Therefore, further inter-connecting themes that focus on networks, actors, and structures also feature in recent STS studies (Castells 2010; Latour 2007).

To realize the full benefits of HRTs, organizations will need to take a holistic, sociotechnical approach—jointly optimizing the technical, personnel, and work design elements in alignment with their specific operational context and values. An STS perspective toward human–robot collaboration and work systems such as those found in construction can be useful in describing the inter-relations among different elements of the systems, across time (life cycles, medium- and long-term impacts of change) and space (spatial, levels, distances).

These views justify the use of qualitative research approaches as they would allow for both interpretative inquiry and qualitative data generation to delve deeply into the understanding of these inter-related systems elements.

3 Research design and methodology

The rationale for the research design and methods of inquiry are elaborated in detail in this section. The research is organized around investigating how different stakeholders or people in the system, or systems conceptualize, organize, develop, and plan to ultimately deploy and work with innovative technologies such as robots in the construction sector. The goal is to provide scholars and practitioners with a preliminary snapshot of STS considerations for translating intelligent robot technologies in practice in planning and deploying collaborative robots in the construction sector.

3.1 Research aims

Through the research questions posed earlier in the literature review, this research aims to:

- Explore how innovative ideas about intelligent robot technologies translate into practice in the construction sector
- Determine roles that various stakeholders play from ideation to deployment in innovation projects providing human robot teaming solutions to the construction sector
- Develop an integrated STS human–robot teaming framework

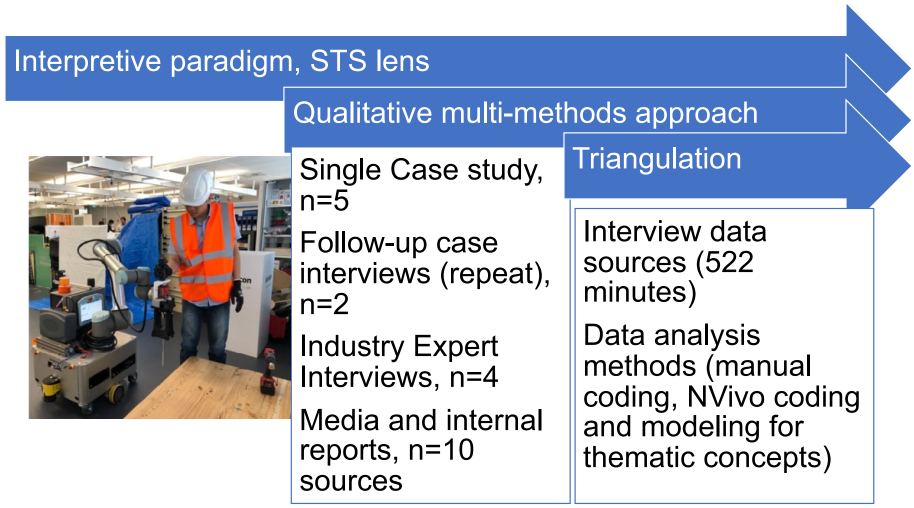
3.2 Methodology

To achieve the research aims, a qualitative multi-methods design was utilized, drawing upon an interpretive philosophical paradigm to examine multiple perspectives. Figure 1 presents an overview of the research design and methodology employed in this study.

The methodology consisted of two key components:

1. A single case study of a network of engineering (Pseudonym: AURORA) and construction organizations (Pseudonym: MAXPRO) and their client (Pseudonym: MODA) who field trialed a robot for screw fixing installation at a timber building construction site.

Fig. 1 Research design and methodology



- Data were collected through semi-structured interviews with key project stakeholders, internal reports, and external media content. This allowed for an in-depth exploration of the case and arising themes from an STS lens.

2. Semi-structured interviews with industry experts not involved in the case study project.

- These interviews with construction stakeholders at different tiers provided additional insights and enabled triangulation of findings.

The study used a single case study to explore human–robot teaming from design to deployment with a comprehensive view from various stakeholder perspectives (Thomas 2006). Case studies as a research strategy and method for generating and testing theory is well accepted and recognized for its strengths in management research (Eisenhardt and Graebner 2007; Yin 2014). This is because case studies can provide real-life, contemporary bounded system (a case) over a set time. Within the case, this study utilized multiple sources of information to offer different in-depth perspectives, thick description, and triangulation (Creswell 2014; Stake 1995; Yin 2014). These data collection methods of inquiry include semi-structured interviews with key project stakeholders, artifacts such as internal reports and external media content to explore the case and its arising themes from an STS perspective.

Specifically, data collection was conducted through interviews with engineers and project members involved in the mass timber construction project, providing insights into the ideation and deployment of HRTs in the construction sector.

Due to the project's on-site completion in late 2022 and the reassignment of workers to other projects, we were unable to interview construction workers directly. While this somewhat limits the scope of perspectives to those in supervisory roles, their in-depth insights remain valuable for understanding the broader social, organizational and technical challenges. The approach is further justified as a single unique case study fits the necessary criteria for theory building as it provides unusual research access (Flyvbjerg 2006), exemplary case (proof-of-concept in practice) and reveals a complete cycle of sociotechnical activity for the industry as suggested by Yin (2009) and Eisenhardt and Graebner (2007). Instead of laboratory experiments where the phenomena (humans working with robots) are isolated from their environment, this case study was selected, because it enables the study of sociotechnical phenomena in HRT technologies within the context of the construction industry. The study of phenomena within their contexts (Gibbert et al. 2008) allows for connections between constructs that will lead to theoretical insights (Eisenhardt and Graebner 2007; Siggelkow 2007). The case of the mass timber construction robot was selected for this study due to the researchers' direct access to the project, which allowed for in-depth insights and first-hand experiences. Unlike other popular construction robots, such as 3D printing robots, drones, or bricklaying robots, the research team had the unique opportunity to closely collaborate with the robotics team and gain access to project members involved in the development and implementation of the mass timber construction robot.

Human research ethics approval (No. ETH22-7525) was obtained prior to starting this study to ensure that the research codes of conduct and protocol are adhered to by all researchers. As part of the human research ethical practice, all participants were provided with adequate information about the research study, ensuring organization and participant anonymity, and participant consent for the interviews to be digitally recorded, transcribed, and analyzed for reporting and publications. In this paper, pseudonyms are applied to the organizations and interview participants to protect their identities for privacy and anonymity.

A brief synopsis about the case study is provided for context and background. This will be followed by a detailed explanation of the data collection and analysis.

3.3 Synopsis of the case

Researchers at the University of Technology Sydney (UTS) developed an autonomous robot (named Quenda-bot) for a timber building construction (Le et al. 2023), in collaboration with MODA (client) and AURORA (construction engineering). Mass Engineered Timber construction is on the rise as timber delivers sustainability and environmental benefits. Building with timber is also faster, quieter, and safer, and produces less waste.

Mass timber construction involves installation of thick and bulky cross-laminated timber (CLT) panels. This requires drilling and screwing hundreds of long screws to connect the panels and ensure the structural integrity of the building. However, installing screw fixings in a timber construction site is a tedious and highly repetitive task that requires precision and accuracy. This can cause fatigue and back injury given the repetitive nature of the job and working in awkward poses. Intelligent robotics provide an innovative solution to address these significant work health and safety issues, while improving efficiency and accuracy leading to higher productivity.

The Quenda-bot comprises of a mobile platform and a 6 degree-of-freedom robotic arm. A custom-designed screwdriver and support mechanism are mounted at the end-effector for purpose of installing screw fixings. The robot's in-built sensors and navigation systems enables it to autonomously navigate and localize itself around a construction site, correlate its surroundings with the Building Information Modeling (BIM) data preloaded into the robot, and make its way to a section where screw fixings need to be installed. Once it reaches the section, the bot calculates the locations of the screws, and moves its robot arm to the desired places while avoiding collisions with the surrounding environment. Then, the Quenda-bot installs the screws into the timber with advanced control methods.

The accuracy and efficiency were reported to have a significant improvement compared to manual installation of the screws. Initial test simulations demonstrate that a 16%-time savings (Internal AURORA report 2021—anonymous) in the overall timber installation program for MODA could be realized, assuming the robot is deployed to install all of the screw fixings rather than humans. The key difference is that humans arrive at an efficiency level after approximately 5 screws are installed, as they require a 'warmup' time, whereas the robot has with an efficient installation speed straightaway from the first screw. Moreover, unlike humans, the robot is not subject to fatigue, only facing downtime when the battery needs recharging. In terms of accuracy, the spacing of the screws was conducted done to ± 1 mm accuracy, which demonstrates improved accuracy compared to human installations of the screw fixing at approximately ± 5 mm (Internal AURORA report 2021—anonymous).

A simple user interface allows workers to monitor the operation of the Quenda-bot and view real-time data. At the point of prototype deployment on site, a human operator was needed to feed the screws to the robot as the self-feeding mechanism was not completely developed due to time constraints. After one section is completed, the robot will autonomously move to the next section for installing more screw fixings.

Figure 2 and the video link provide further information about the robot technology, and the human and robot collaborating as a team in the construction task: https://www.youtube.com/watch?v=YGoa9ZIdxDw.

4 Data collection and analysis

4.1 Semi-structured interviews

4.1.1 Participant profiles and sampling approach

In qualitative research, the focus is on purposive sampling to select participants with certain characteristics that are important to the study's purpose, rather than probability sampling which is common in quantitative research (Hennink et al. 2020). Robinson (2014) in a guide on sampling in interview-based qualitative research suggests that researchers, 'based on their *a-priori* theoretical understanding of the topic being studied, that certain categories of individuals may have unique, different or important perspective of the phenomenon in question'. (p. 9). The sample size is not as critical as the quality and diversity of the sample, which should be chosen specifically to gather in-depth and diverse perspectives, capturing the variety of experiences relevant to the study's objectives (Hennink et al. 2020).

The anonymised profiles of the five project members interviewed for the case study can be found in Appendix Table 3, while the profiles of the four industry experts interviewed can be found in Appendix Table 4. The industry expert interviews comprised of construction stakeholders at different tiers (e.g., construction consultants, project engineers, and industry educators). They were selected based on their cross-disciplinary experience, senior positions, and expertise in the fields of construction management and advanced technologies. Together with the secondary data used, theoretical saturation was achieved (Bryant and Charmaz 2007).

Snowball sampling (Patton 1990) was used, since this approach is useful for locating information-rich key

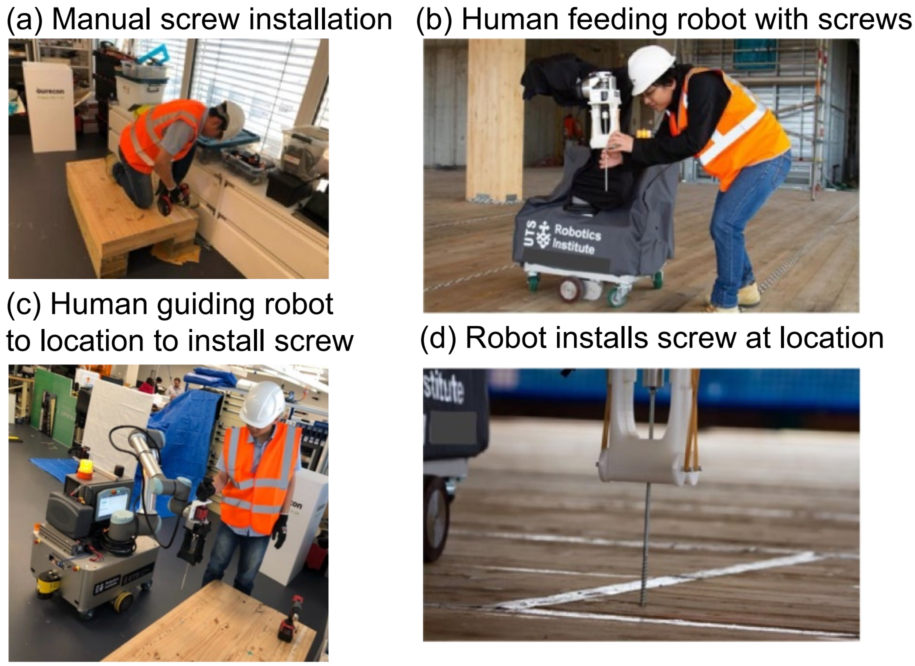


Fig. 2 Image of the case study robot technology deployed

informants. The authors are aware that this type of sampling cannot be considered for a representative sample; however, this sampling technique is useful in qualitative research for qualified informants that might otherwise be difficult to find. The authors also ensured that the participants were diverse in their roles and from different organizations (Appendix Table 5).

4.1.2 Sampling size and saturation

In the semi-structured interviews, the sample size was determined by considering the diversity of informants who could provide rich information and elaborate on the three levels of analysis: macro, meso, and micro. The combination of five case study participants and four industry experts allowed for triangulation of findings from different viewpoints. Nine semi-structured interviews were considered sufficient given that the different participant responses are triangulated against each other. This approach aligns with the concept of "meaning saturation" (Hennink et al. 2017), where the aim is to develop a richly textured understanding of the issues rather than merely reaching "code saturation" by identifying a range of thematic issues.

In this study, the sample was determined by considering the diversity of informants who could provide rich information and elaborate on the three levels of analysis: macro, meso, and micro. At the macro-level, the Case Robotics Director DISHKA and Industry Experts MEKA, JAKA, and ADKA contributed strategic insights on visionary leadership, change management, feasibility, and stakeholder buy-in.

For the meso-level, the Case Project Lead Engineer PRAKA, Case Robot Engineer-Hardware ALKA, Case Robot Engineer-Software GIKA, and Industry Expert AFKA provided valuable perspectives on planning, designing, developing the robot, and managing operations. Their inputs covered aspects, such as mediation of collaborative networks, workforce readiness, and safety considerations.

At the micro-level, the Case Construction Consultant PEKA shared experiences related to the on-site deployment and collaboration with the robot, offering a practical understanding of task execution and human–robot interaction.

While the sample size of nine participants may seem small, it is consistent with the recommendations for reaching code saturation in qualitative research, which can be achieved with as few as 7–12 interviews (Hennink et al. 2017). Moreover, the study's focus on a single unique case that provided unusual research access, an exemplary proof-of-concept, and a complete cycle of sociotechnical activity justified the smaller sample size (Eisenhardt and Graebner 2007; Flyvbjerg 2006; Yin 2014).

4.1.3 Interview protocol and data collection

For transparency and traceability, this study established a systematic and clear chain of evidence to provide construct validity taking the reader through research procedures and protocols, so that the case can be reconstructed to determine how this study arrived at its final conclusions (Eisenhardt and Graebner 2007; Yin 2014). To achieve this, the interviews followed a semi-structured interview protocol. The interview protocol ensured that the flow, key questions, and topic areas were covered consistently and comprehensively, with guidelines to ensure that the sessions allowed for an open and confidential discussion. A list of questions was provided to participants ahead of the interviews. At the beginning of the interview, extracts of a video about a collaborative robot performing a task with a human worker was shown to the participants.

This helped to visually provide some context for industry experts to focus on a specific type of robotic technology for construction. This also helped to compare the industry expert perspectives with those of the case study when discussing similar technologies and contexts for triangulation purposes. A follow-up interview after 18 months with the robotic developers complemented the earlier findings (Ang et al. 2023). Average interview duration was 50 min yielding 522 min of interview data collected.

4.2 Public documents, reports, and media sources

Publicly available documents from various media sources (news articles, videos, and TV reports), confidential organization reports, and robot technology specifications were used to establish the background and context of the case. Specific references to these sources are not cited to maintain the anonymity of identities of the organizations and their members.

From data collection, the interviews and audio from media were digitally recorded and professionally transcribed into a text format for analysis.

4.3 Data analysis

The attention given to developing constructs, measures and theoretical propositions allows an inductive case study to be aligned with normal-science streams of research (Eisenhardt and Graebner 2007). A combination of deductive and inductive coding techniques using Nvivo (software used in qualitative computer-assisted data analysis) was applied to construct the themes and patterns in the data. Through an iterative process, parent and child codes were grouped and regrouped into macro-, meso-, and micro-clusters. Various Nvivo tools were applied to query and visualize the data and its networks in different ways. Figure 3 is an example of interpretative analysis involving child and parent nodes visualized as clusters and networks. The sunburst hierarchy diagram visualizes the distinct three constructed levels or clusters.

5 Findings

From an STS perspective, the human–robot collaboration for the task involves more than just humans working with a robot to drill and install screws into timber; it is one of many interactions within the broader sociotechnical system and its interconnected systems.

One of the interviewees, Industry Expert 4 ADKA described that there are various levels of tasking in a system separated by humans and robot tasks "*management and supervision tasks by the people, execution tasks with the robots*." (Industry Expert 4 ADKA). The data analysis and model in Fig. 3 shows that there are multiple levels of STS considerations. These levels of human inter-relations at the Macro-, Meso-, and Micro-levels impact on the ideation process and considerations of how it translates into design, development, and deployment of robot technologies into a construction site. The social actors (humans) in the system interact at 3 main levels: the macro-level (organization and senior management), meso (planning, designing and developing the robot, operations management and supervision, and micro-level (deploying and implementing the prototype onsite with human operators and laborers). Each level has its set of challenges and considerations critical toward the successful deployment of robot technologies in construction and will be presented in Fig. 4.

Figure 4 provides a simplified view of the inter-relationships between the levels and shows how certain actors connect the levels. The organizational stakeholders in intelligent robot development from Planning and Design to Prototype Deployment was illustrated (Fig. 5) and described in detail in a previous paper (Ang et al. 2023, p. 296).

The following section elaborates on the three system levels in more detail. Further analysis at the other levels and the quotes that support the analysis can be provided upon request.

5.1 Macro-level

The Macro-level oversees the whole project, with a bird's eye-view of the complete translation of vision, intent, and strategy to implementation, with comments such as *'Let's make it happen' (Case Project Lead Engineer PRAKA) and 'Bring it on' (Construction Consultant PEKA)*. The active participants at the Macro-level are the Senior management, mediator/project lead, Client (investor) and Strategic collaborators, decision-makers, and consultants.

When asked about what factors need to be considered when translating an idea or vision to deploying robot technologies at a construction site, one of the industry experts suggested adopting a more holistic view, *"Look at the company and the organization as a whole rather than individual tasks …. then go to the task level and decide where you would use those robots"* (Industry Expert 3 AFKA).

At the macro-level, interview participants generally indicated the following considerations that are mainly organizational and strategic in nature: Visionary leadership and commitment, change management, the extent of collaboration

Fig. 3 Clusters of parent and child nodes visualized as sunburst hierarchy diagram of macro-, meso-, and micro-level considerations

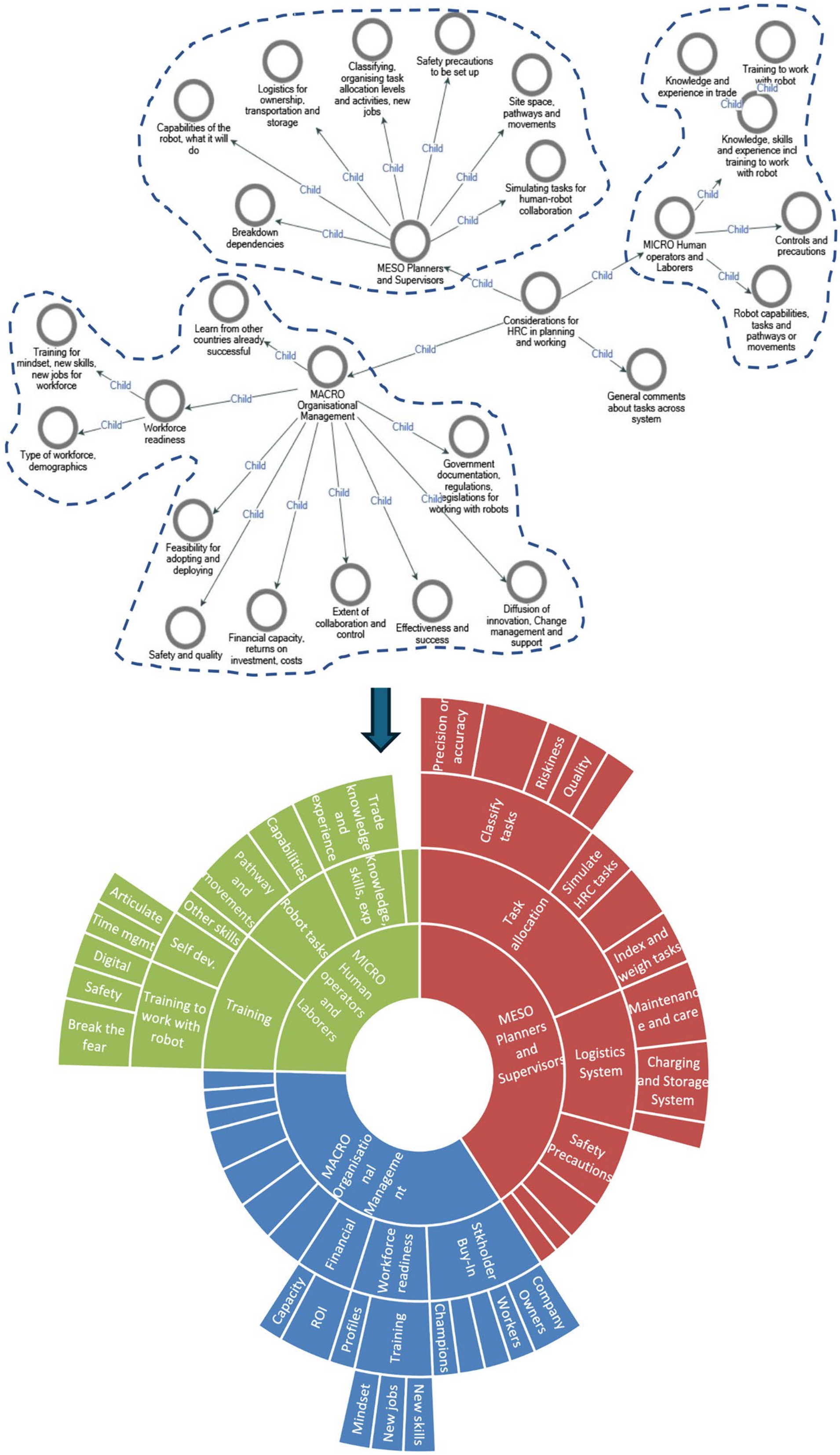


Fig. 4 Inter-relationships across the macro-, meso-, and micro-STS levels that translate the vision of technology to deployment on site

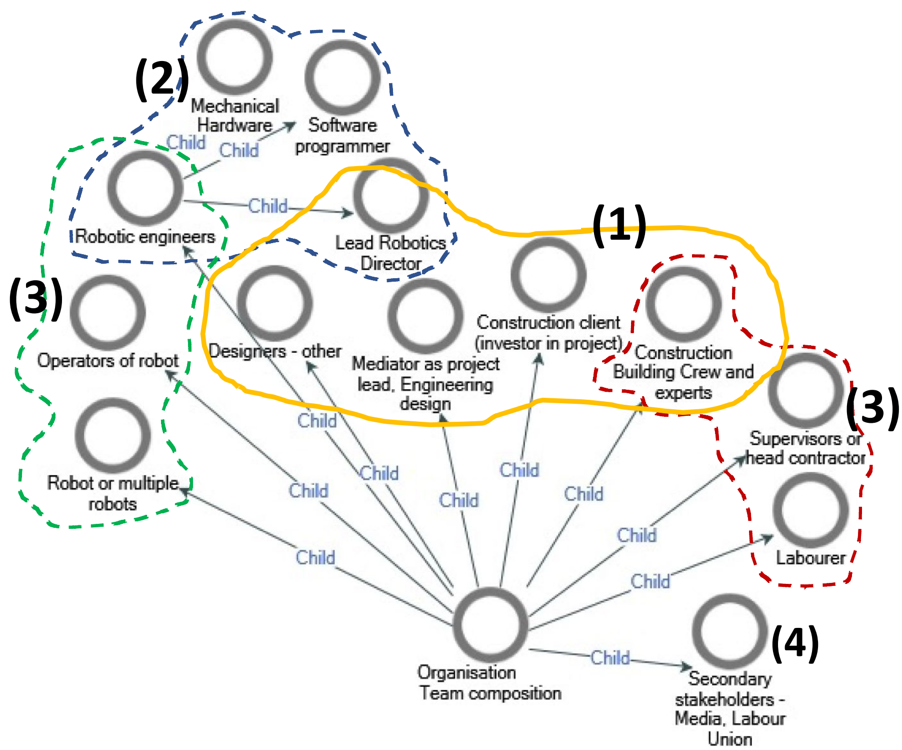


Fig. 5 Organizational stakeholders in Intelligent Robot development, Ang et al. 2023, p.296

and control with robot technologies, feasibility of the organization for adopting and deploying including culture, financial capacity and expected returns on investment, and government regulations and legislations about working with robots, safety, and quality.

5.1.1 Visionary leadership and commitment

The necessity of visionary thought leaders and commitment to effort in translating ideas into practical solutions was emphasized as key to translating any idea into an innovative solution in practice, as commented by Robotics Director DISHKA, "*you need to have both vision and effort to make it happen*".

Furthermore, DISHKA indicated that the vision needed to be championed by thought leaders who would also drive the efforts to make it happen. This was not a single individual but required the commitment and contribution of many individuals, as commented by DISHKA, *"basically many people contribute to it. It's not only one or two people."*

5.1.2 Change management

Participants mentioned the importance of managing change rather than merely introducing robots (e.g., Industry Expert 4 ADKA); however, others stated that the pace of change occurs slower in people (mind) and organizations/social (culture) compared to technological change (e.g., Robotics Director DISHKA).

5.1.3 Feasibility and readiness

The feasibility and readiness of implementing a robot were highlighted by considering both the micro view of task analysis and the macro-view of organizational analysis. This involved evaluating whether an organization of a particular size, level of innovativeness, workforce, and training capacity would be suitable for integrating a robot (Industry Expert 3 AFKA).

5.1.4 Stakeholders buy-in

It was also important for decision-makers to recognize the credibility of the innovation and identify success stories prior to adoption. Stakeholder Buy-In to the technology was necessary for successful deployment. These would include the project owners or clients, workers, and the industry. An interviewee (Industry Expert 1 MEKA) suggested that having a credible advocate could facilitate the deployment process. This advocate should come from the same professional background as the users, for example, a highly respected and experienced welder who has successfully adopted and endorses the use of a robot welding machine. Their endorsement could encourage others to give the new technology a try.

5.2 Meso-level

The meso-level in the system deals with planning, designing and developing the robot, operations management, and supervision. The active stakeholders at this level tend to be the project managers, contractors, line managers, planners, schedulers, and supervisors.

At the meso-level, the complex interplay between stakeholders can give rise to unexpected dynamics as they collaborate to design, develop, and manage the integration of robots onto the work site. Conflicting priorities, communication gaps, or resistance to change among these stakeholders may surface, requiring adaptive leadership and proactive issue resolution to keep the project on track.

Case Project Lead Engineer PRAKA suggested that early engagement and open dialog with various stakeholders and key actors were deemed critical. Initiating discussions early and inviting stakeholders to review and provide feedback on the plan can initially meet resistance.

The technical limitations or capabilities of the robots may necessitate unforeseen or unanticipated adjustments to operational processes, team structures, or job roles at this level. Planners and managers will need to remain vigilant to identify and address these unforeseen impacts on workflow, resource allocation, and task coordination between humans and robots. However, maintaining continuous dialog is essential to ultimately achieve the project's goals.

5.2.1 Mediation of collaborative networks

Findings show that the mediator and project lead play a crucial role in driving the design and planning at a macro-level that bridges with the meso-levels of operations. The mediation and collaborative design thinking sessions organized by the Case Project Lead Engineer PRAKA effectively engaged various participants, including designers and contractors, as consultants. This approach contributed significantly to the project's success. Consultant PEKA confirmed that the team, consisting of design managers, drafting personnel, project managers, and engineers, was consulted on the constructability of the project and its connections, and enjoyed participating in design meetings with teams from Germany, Italy, the East Coast, and the MAXPRO design team, which led to a fantastic result.

Case Project Lead Engineer PRAKA was praised for being an exceptional team organizer, effectively structuring meeting minutes to keep everyone aligned. This sentiment was echoed by Case Robot Engineer-Software GIKA, who emphasized that the collaboration with the AURORA group was key to developing the robot.

5.2.2 Workforce: readiness and profiles

The next area of consideration is workforce readiness, which involves training for new skills, addressing workers' fears of working with robots, and assessing their capabilities for different types of new jobs. Industry Expert 3 AFKA noted that as robots take over part of the work, the freed-up time should be used for workers to expand their skills and contribute more to the company's economy, and commented, "*If 20 to 30% of the job is automated, new jobs must be created to retain the existing workforce*".

These considerations must go together with identifying the profiles of workers at macro-, meso-, and micro-levels to assess their readiness and determine appropriate jobs and training. At the operational or meso-level, Industry Expert 4 ADKA emphasized that as part of the educational process, it is important to understand the diversity of the workforce, including their locations and characteristics. For example, in regional Australia, an aging workforce with limited skill sets might react differently compared to younger individuals who are more familiar with technology like iPads and might be more enthusiastic about working with robots.

5.2.3 Safety and quality: fundamental considerations

Safety and quality are essential in any construction organization, as noted by Industry Expert 2 JAKA. He explained that decisions often consider Health, Safety, and Environment (HSE) factors, cost elements, and work quality, with organizations needing to address all these aspects. Robotics Director DISHKA reinforced the fundamental importance of safety when humans and robots share a dynamic work environment, "*Safety is a very important and complex issue in this scenario*". He highlighted the complexity of ensuring safety for people, equipment, robots, and construction sites, including floors, columns, and the overall environment.

Since the beginning of their work in robotics technology, efforts have focused on safety through advancements in sensing, perception, and reliability, ensuring the safety of human workers, robots, structures, and the environment.

5.3 Bridging the meso- with the micro-levels

The importance of understanding task planning and how it bridges onto the micro-level is raised by Industry Expert AFKA who offered an objective solution to enhance how workers and robots can work together for onsite tasks, *"We could draw a schematic plan to demonstrate such human–robot collaborations and pathways. We need to have such new plans in the project to systematically facilitate adoption of co-bots in future."*

5.4 Need for learning and adaptation at all levels

Hardware engineer ALKA suggested that stakeholders must learn to control and adapt to intelligent robotic technologies within their organizations, "…*because they are adapting technology with new people"*. Each company or group will need to develop its own unique approach to managing and utilizing these robots effectively. This sociotechnical process of learning and adaptation will be necessary at all levels: the macro-level of the organization, the meso-level of specific departments or teams, and the micro-level of individual employees. This implies that embracing these technologies will require significant effort and flexibility from stakeholders across the board.

6 Discussion

Considering advancements in technology, the key perceptions are that organizations investing in robot technologies focus primarily on productivity and competitiveness. Incorporating sociotechnical perspectives from robot design to deployment, enables a more sustainable implementation of Industry 4.0 within an organization (Sony and Naik 2020). As we transition into the era of Industry 5.0 that merges the high speed, powerful and accurate machines with creative, critical, and cognitive thinking of humans, it is expected that human–robot teams will enhance performance and quality by assigning repetitive and monotonous tasks to the robot and higher cognitive functions to humans (Raffik et al. 2023). The overarching research question (RQ1) is addressed, "*How do innovative ideas about intelligent robot technologies translate into practice in the construction sector?"* in the ensuing discussion. This is followed by discussions addressing RQ2 and RQ3.

6.1 Macro-level: stakeholder engagement, mediation, and industry preparedness

6.1.1 Mediation and early stakeholder engagement

From the findings, STS at the macro-level starts with early engagement, structured design thinking sessions, and open conversations held with the different key actors. It reflects the STS interplay of actors, organizations, networks, and the system itself. Certain actors take on critical roles in the transformational and innovative endeavor, such as the project lead as the mediator. For instance, the literature supports the need for actors to mediate actively to organize sociotechnical systems change, interpreting and reinterpreting the change, rather than passively diffuse a set of ideas and practices (Sørensen and Torfing 2016). Mediators also play a key role by providing a single point of contact for all other actors (Bessant and Rush 1995), where the organization gains access to a wide range of specialist services (e.g., robot engineers, timber consultants, and building designers). The case study demonstrates that a visionary leader and mediator at the macro-level equipped with organizing, strong communication, good coordination, and collaborative capabilities across a network of specialists can facilitate and engage stakeholder support and buy-in. This helps to ensure a successful translation of a vision into a proof-of-concept application in the field.

6.1.2 Facilitate industry preparedness for emergent technologies

Organizations and the industry need to consider government regulations and legislations for robot deployment onsite. However, Berx et al. (2022, p. 11) questions whether the legislation will be sufficiently agile and adaptable to at least "keep track of risk factors emerging from continuously changing technologies and to translate them into practically applicable tools for enterprises and design engineers implementing collaborative applications". The authors suggest that government agencies and industry bodies need to be consulted and engaged in the development process to facilitate industry preparedness and translation.

While it is recognized that application of robots could drive industrial transformation as supported by Yang et al. (2019), the uptake of construction robots is still limited in practice. The construction industry is viewed as conservative, and generally less ready to adopt robotic technologies. Design engineers have been working on construction solutions to address the problems of worker safety and productivity by developing innovative robot technologies (Bock 2015; Gharbia et al. 2020; Xiao et al. 2022). Yet, advanced automation such as robot technologies are not readily adopted due to conservative mindsets, fear or distrust of robots, loss of jobs, costs, and liability to name a few found in the construction industry. Stakeholders buy-in at different systems levels need to be considered. This is in line with several recent views (Kim et al. 2022; Liang et al. 2024) that for successful integration, robotic roles need to address stakeholder concerns, and align with stakeholder needs and job characteristics. These concerns must be proactively managed to ensure responsible implementation and workforce acceptance of new technologies.

6.2 Meso-level: emerging competencies, work design structures, and readiness

With the introduction of robots in construction, management and workforce preparation through education, skill development, training, standardized protocols, and mindset readiness are important considerations, as new areas of exploration in robotics research that require more attention in HRC (Jipp 2016; Pan et al. 2018; Parker and Grote 2022). This includes workers' involvement and participation, particularly throughout the risk assessment and mitigation cycle (Berx et al. 2022), training programs, and protocols for human–robot interactions (Pan et al. 2018). Facilitating change through the design and deployment of cutting-edge robotics technology in the construction sector needs to also happen in an integrated way at the macro- to meso-levels. Different cognitive demands required of workers and managers are likely to require different competencies to cope with and adapt to the adoption of robotics across different organizations with different structures and cultural environments. Planners, schedulers and operations and logistics management also need to understand how human–robot collaborative processes function to suggest alternative work design including routines and tasks that are safe, ethical, efficient, and effective.

With workers freed up and potentially allocated new or alternative tasks, the risk of losing their traditional trade skills is likely. However, they are also likely to develop different digital and higher level capabilities. This is in line with the literature that human cognitive performance is affected through deskilling as pointed out in an NASA Air Space program report (Sheridan and Nadler 2006) when physical workloads are being replaced by cognitive workload like problem-solving, monitoring, and controlling robot operations.

6.3 Micro-level: early involvement, team performance, and emergent novel relationships

6.3.1 Involvement of micro-level stakeholders in design and development

Norman and Stappers (2015) remarked on the tendency of design for complex sociotechnical systems to revolve around technological requirements. If the system design expects the worker to do tasks, they might be ill-suited for or have not been well-trained and briefed on, this could create room for human error that potentially jeopardizes safety, increases waste or damage. In this case study, worker interaction was limited, or they were distanced from the robot. If the workers were briefed or trained on the tasks of operating and cooperating with the robot, the performance scenario could be different.

The human worker's task in this case study was to feed the screws to the robot, and to monitor the robot's activity through a graphic user interface to administer the Start–Stop controls. While it seems beneficial that the Start–Stop or E-Stop emergency function could be operated remotely from anywhere, this could also imply that people are expected to monitor events for potentially long periods where they are inactive. Then, they are expected to respond and act promptly should some aberration or malfunction occur (Norman and Stappers 2015). The latter, in view of a 'response system' requires further development from a social view.

6.3.2 Understanding nuanced scenarios to enhance performance

As the 'brains of the robot', the robotics developer (programmer) is required to ensure that the robot performs with accuracy and precision in accordance with the trade craft skills, blueprints provided and as expected by robot technologies. However, this requires the developer to be capable of an accelerated understanding the trade and its unique nuances for the robot's performance in different scenarios. This was also the way in which a better expert system was developed to diagnose if a vehicle developed for a defense organization could be troubleshooted in the field (Tay 2003). The software engineers who were developing the program were asked to drive the vehicle for which they were building the expert system to get to know the requirements better.

6.3.3 Emergent and novel relationships

As the construction industry considers and adopts HRTs, new patterns of interaction and interdependence between workers and intelligent robotic technologies could organically emerge beyond initial intentions. For instance, workers may adapt and develop novel workarounds to operate the robots more efficiently, leading to bottom-up process innovations.

Alternatively, certain technical constraints of the robots might unexpectedly hinder certain tasks, requiring workers to compensate through increased manual effort or creative problem-solving. These emergent relationships can alter the nature of work and the division of labor between humans and robots in subtle but significant ways, with implications for job satisfaction, skill requirements, and team dynamics. Organizations will need to closely monitor and learn from these organic developments to optimize human–robot synergies over time.

6.4 Human–robot collaborations and teaming

Considering the discussions about how micro-level human–robot teams might work in practice, a spectrum of human–robot collaborations and teaming that can be conceptualized through a hierarchical framework where designers need to consider for operations, ranging from the robot functioning independently of humans to a fully interactive and collaborative synchronous engagement with humans is proposed. This addresses the third research question about '*How might human–robot teaming be characterized and operationalized in the construction sector'*.

Based on the review and discussions so far, Christiernin (2017) suggested four distinct levels or hierarchy of collaboration in designing and implementing human robot collaboration (HRC): no collaboration (level 0), stop/start (level 1), interactive (level 2), and collaborative (level 3). Based on the findings on human–robot teaming, we suggest adding another level as shown in Fig. 6. The levels in the schema are explained in the following paragraphs.

At the lowest level (L-0), characterized by no collaboration, robots operate in isolation within a designated space inaccessible to humans, similar to traditional caged or gated robots. Moving up to stop/start interactions (L-1), the robot remains idle and inactive when humans are present in the workspace, such as holding a workpiece, while the human performs manual tasks. Human control tends to be limited to starting or initiating and stopping or concluding automation routines.

Interactive HRC (L-2) involves a synchronous relationship where humans guide or influence the robot's actions using input methods like steering, voice commands, or sensor activation. The robot, in turn, adjusts its activities to avoid collisions with humans by tracking their movements.

The Adaptive-Collaborative (Level 3) represents high-level interactions that would be reflective of the nature of a team, where humans and robots dynamically collaborate on joint tasks, with the robot adapting and learning from observing human actions. This level suggests joint optimization, intelligence, advanced sensing, and task modeling capabilities to grasp human intent and social cues, fostering an adaptive and dynamic collaboration in the team. Levels 2 and 3 show more intuitive interactions, departing from pre-programmed and scripted sequences to accommodate diverse robot actions based on human and environmental feedback.

Through the lens of STS and considering the growth of artificial intelligence (AI) and LLM can potentially lead to the emergence of Level 4 in collaborative human–robot

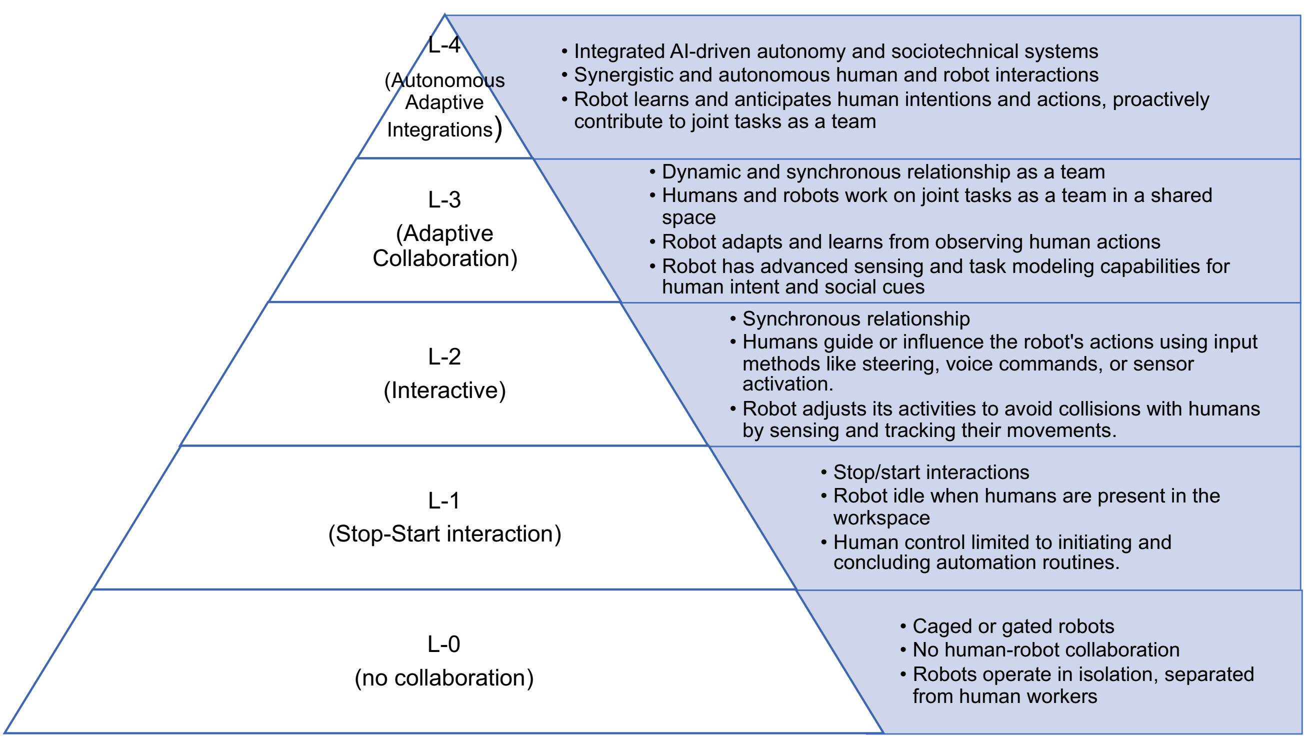


Fig. 6 Extended hierarchy of human–robot teaming (inspired by Christiernin (2017)

teams. At Level 4 (Autonomous Adaptive Integrations), the collaboration between humans and robots as an integrated team could be characterized by a seamless integration of AI-driven autonomy and STS. In this advanced level, for greater compatibility and joint optimization, the team dynamically adapts to each other's actions, the task and workflow requirements, and the changing environment on the construction site. They fluidly switch roles as needed.

AI and LLM play a crucial role in enabling robots to autonomously adapt to dynamic environments, human behavior, and changing task requirements beyond scripted pre-programmed functions. The collaboration ideally transcends mere responsiveness to become a synergistic interaction where the robot would have a high degree of autonomy and decision-making ability to respond to the dynamic, unstructured construction environment. In addition to anticipating human intentions and actions, it would be able to handle uncertainty and ambiguity and proactively contribute to joint tasks.

The robot and human could engage in rich multimodal communication, including natural language, gestures, and shared context awareness to coordinate their activities seamlessly.

The robot learns and improves its performance over time by observing the human, getting feedback, and gaining experience.

Construction sites are highly dynamic, unstructured environments requiring a lot of adaptability, situational awareness, and close coordination between team members. An adaptive team mode where the robot can flexibly collaborate with humans as an equal team member, handle uncertainty, and improve through learning would be very valuable. This goes beyond simple interactions to deeper integration and teaming.

The STS approach detailed in this study could ensure that HRT collaboration considers not only technical aspects but also the social (e.g., work roles, well-being, autonomy as a team, agency, participation, and decision-making) and organizational context in which it operates. STS thinking emphasizes joint optimization of the social and technical subsystems, where the Level 4 integrated and adaptive teaming enables the human and robot to leverage their complementary strengths to accomplish construction tasks effectively as an integrated whole. In the design of the HRT work system, the users' capabilities in terms of skills and limitations need to be considered. From this basis, a micro-level workplan schema is suggested in Table 1 that covers the application of novel ideas such as intelligent robot technologies at different hierarchy levels of collaboration for the construction sector.

In this discussion, the study has examined the translation of novel ideas into practice in the construction sector and the diverse roles played by stakeholders throughout the ideation to deployment process in human–robot teaming solutions. The study highlighted the expectations that HRTs could enhance performance and quality by assigning repetitive tasks to robots and cognitive functions to humans. The study highlights the role of human workers, developers, and the necessity for proper training and briefing to avoid potential errors. The study has also raised the need for government regulations for new technologies, workforce preparation, and the potential loss of traditional trade skills.

6.5 A holistic view of HRT incorporating the macro-, meso-, and micro-levels

An integrated view of humans and robots collaboratively working as a team or HRT can be summed up in the following framework in Table 2.

Overall, the study has provided a holistic view of the roles played by stakeholders at various levels—macro, meso, and micro; ensuring a comprehensive understanding of the dynamics involved in innovation projects. The overlapping functions, inter-connections, and inter-dependencies across the macro-, meso-, and micro-levels are important to consider in integrative STS studies that reflect heterogeneous and non-linear multi-directional characteristics.

In addressing the second research question, "*What roles do various stakeholders play from ideation to deployment in innovation projects providing human robot teaming solutions to the construction sector?*", the discussion emphasizes the need for active leadership and mediation at the macro-level, showcasing how a visionary leader can facilitate stakeholder support and buy-in, ensuring the translation of an idea into a proof-of-concept application. Leadership and mediation combined with commitment and effort by the various stakeholders are key for successful implementation and translation of ideas about emerging technologies into practical applications. Furthermore, the role of the project lead as a mediator orchestrating the interplay of actors, organizations, networks, and the system itself is crucial, as is the involvement of specialists such as robot engineers, timber consultants, and building designers. Additionally, the study reveals the importance of government agencies and industry bodies in the development process, considering regulations and legislation for robot deployment. The study contributes an integrated hierarchy of intelligent human–robot collaborations for HRTs (Fig. 6) that is accompanied by an alternative workplan schema (Table 1) depicting how each level in the hierarchy might function. Finally, the integrated human–robot teaming framework (Table 2) demonstrates how novel ideas about intelligent robot technologies could translate into practice in the construction sector.

Table 1 Micro-level HRT workplan schema

Across all micro-levels	Levels in the hierarchy	Workplan schema
Safety Protocols • Implement safety protocols to ensure the well-being of workers User Training • Provide training programs for workers to effectively collaborate with robots • Training for supervisors or team leaders / coordinators to manage work processes across human–robot teams Feedback Mechanisms • Establish feedback mechanisms for continuous improvement and system optimization	Level 1: Stop/Start Interaction	• Task Segmentation: Define specific tasks suitable for automation and human intervention • Automation Routines: Develop basic automation routines that can be started and stopped by human input • Work-space Monitoring: Implement sensors to detect human presence for ensuring safe interactions
	Level 2: Interactive Collaboration	• Input Methods: Introduce various input methods (e.g., steering, voice, sensors) for human guidance • Adaptive Robotics: Enhance robot capabilities to adapt activities based on human input and movements • Real-time Communication: Implement real-time communication interfaces for human–robot coordination
	Level 3: Collaborative HRT Interaction	• Task Understanding: Develop advanced sensing and task modeling for the robot to understand human intent • Learning Mechanisms: Implement learning algorithms allowing the robot to adapt through observing human actions • Adaptive Collaboration: Establish bidirectional responsiveness, where both human and robot dynamically adjust to each other
	Level 4: Autonomous Teams with Complex Adaptive Integration	• Autonomous Decision-Making: Integrate AI algorithms for autonomous decision-making by the robot as part of the team • Adaptive Learning Systems: Implement systems for continuous adaptive learning by the team based on interactions and feedback • Flexible Task Allocation: Develop mechanisms for dynamic task allocation considering human and robot capabilities • Ethical Framework: Introduce ethical guidelines and considerations in AI-driven decision-making processes • Context-Aware Collaboration: Enhance collaboration with a system that understands and adapts to the broader context

Table 2 Integrated human–robot teaming framework diagram

1. Macro Level: Vision to Implementation	Intersections between Macro and Meso Levels	2. Meso Level: Expert Knowledge and Task Planning	Intersection between Meso and Micro Levels	3. Micro Level: Task Execution and Team Collaboration
●Visionary Leadership and Commitment ●Change Management ●Feasibility and Readiness ● Stakeholder Buy-In ●Safety and Quality ●Mediation of Collaborative Networks ● Workforce–Readiness and Profiles	Translating vision into tangible outcomes: Robot design and development	●Expert Knowledge of Tasks and Requirements ●Robot's Capabilities, Operability, and Functions ●Planning of Tasks and Pathways ●Workforce Readiness and Profiles	Task and Pathway Planning and scheduling	●Task Segmentation ●Automation Routines ●Work-cell Monitoring ●Input Methods ●Adaptive Robotics ●Real-time Communication ●Task Understanding ●Learning Mechanisms ●Responsive Collaboration
Across all levels ● Learning, continuous improvement and adaptation at all levels: Training, feedback mechanisms ● Safety and well-being considerations				

7 Future directions and research limitations

Based on the findings of this research, future research on emerging technologies for construction automation should examine new work routines and different job designs for the workers across different scenarios and contexts. Systems designers and engineers could adopt a more holistic and integrated view of the inter-dependencies among the actors and the required skills and capabilities at the different STS levels.

Investigating industry and organizational maturity levels, technology and organizational culture, readiness, and change management practices from an STS perspective could provide insights into the expectations, acceptance, adoption, and deployment of intelligent technologies in HRTs. Another area for future research is to explore the social impact of replacing physical workloads with cognitive workloads such as problem-solving, monitoring, and controlling the robot operations.

The limitation of this study is that it is a single case study about human–robot teaming in the construction sector, approached from a sociotechnical perspective, which is still in its infancy in practice, and not yet well researched in scholarly circles. To address this limitation, we triangulated viewpoints from the case study with in-depth interviews from four industry experts external to the case study. The sample size was also limited due to the scope and time constraints for this project as well as availability of people who worked on the post-hoc nature of this investigation. We were unable to interview construction workers directly due to the project's completion and the workers moving on to other assignments. Instead, we conducted interviews with supervisors, who provided valuable insights into the integration process and its challenges. Future research should aim to include construction workers' perspectives to offer a more balanced understanding of the potential challenges and anxieties related to robot integration.

Moreover, future research could benefit from studying the phenomenon from the outset by encompassing the entire process from the initial discussion of client needs to the conceptualization, development, and delivery of the solution by the research team.

We acknowledge that the complex project and dynamic organizational environment that included multiple internal and external stakeholders, and inter-organizational collaborations across different disciplinary areas may yield different outcomes and conclusions in other fields and scenarios. Nevertheless, this case study serves as a basis for expanding research to achieve broader generalizability and deeper insights into the sociotechnical dynamics of human–robot teams in the construction sector.

8 Conclusions

Most STS studies about robot technologies with human workers tend to discuss the micro-systems of human–robot collaborations onsite. This study advances STS research in the context of human–robot collaborations by providing a comprehensive view of the considerations at the macro-, meso-, and micro-system levels, tracing how an innovative idea translates into a novel robotics technology solution involving human–robot teams in practice. The study highlights that each level does not operate in isolation and requires embracing an integrated STS view.

Addressing the first research question of how innovative ideas about intelligent robot technologies translate into practice in the construction sector, this study suggests that STS in construction should be viewed from multiple systemic levels of interaction—macro-, meso-, and micro-levels within an organization and across organizational networks. The dynamic nature of the construction environment necessitates considering safety, logistics, facilities, and adaptable regulations and policies for emerging technological fields. The proposed ‘Integrated Human–Robot Teaming Framework’ (Table 2) demonstrates how ideas about intelligent robot technologies could translate into practice in the construction sector.

In response to the second research question regarding the roles of various stakeholders, this study emphasizes the need to adopt STS principles in planning, developing, and deploying robotics applications for the construction sector due to its unique characteristics. The findings suggest that multiple elements need to be integrated throughout the ideation, planning, design, development, and deployment stages, involving myriad interactions of multiple actors across the robot deployment lifecycle. The presence of a visionary driver and a mediator as a single contact point for these complex networks coupled with a commitment to effort can potentially facilitate a successful outcome.

Finally, addressing the third research question on how different levels of human–robot collaboration and teaming can be characterized and operationalized in the construction sector, the study presents a workplan schema (Table 1) that outlines the range of considerations based on the levels of human–robot teaming from basic Stop–Start interactions (Level 1) to Autonomous HRTs with Complex Adaptive Integration (Level 4). This schema, along with the proposed hierarchy of human–robot collaboration (Fig. 6) and the Integrated Human–Robot Teaming Framework (Table 2), contributes to the understanding of how HRTs could be effectively implemented in the construction sector and offers practical guidance for researchers and practitioners seeking to navigate the complex sociotechnical landscape of implementing intelligent robotics technologies in this sector.

Appendix

See below the Table 3, 4, 5.

Table 3 Organization of topical categories in analysis

Case Participant identification	Role and responsibilities
Case Robotics Director DISHKA	Director of the robotics engineering team
Case Robot Engineer-Hardware ALKA	Mechatronics engineer responsible for hardware development of the robot technology
Case Robot Engineer-Software GIKA	Senior software engineer responsible for programming the robot technology
Case Project Lead Engineer PRAKA	Project lead engineer and mediator for the overall project
Case Construction Consultant PEKA	Timber construction consultant and contractor in the installation of the timber components
AURORA	Engineering Construction Firm
MODA	Construction Client
MAXPRO	Building Construction Organisation

Table 4 Profile of Industry experts interviewed

Industry participant identification	Qualifications and experience	Role and responsibilities
Industry Expert 1 MEKA	Degree in Construction Management, Master's and PhD in Computer Science 30+years' experience in the construction sector	Senior project manager in a large construction firm, and consultant in the built environment
Industry Expert 2 JAKA	Degree in Civil Engineering 19+years' experience in construction and infrastructure projects in Egypt, Middle East and Australia	Project controls lead—planning, scheduling, and cost control
Industry Expert 3 AFKA	PhD in construction 22+years' experience in the construction and infrastructure sectors	Senior lecturer—Research and teaching in Construction and the Built Environment, specializing in timber construction, design teams, site establishment and management
Industry Expert 4 ADKA	Master of Business Administration 20+years in the oil and gas, mining, construction and infrastructure sectors Regions worked include Southeast Asia (e.g., Indonesia, Malaysia), China, Australia, USA, Europe (e.g., Netherlands)	Director for Infrastructure consultation, Engineering consultant in megaprojects and data strategy

Table 5 Organization of topical categories in analysis

	Categories (Lofland et al. 2022; Saldaña, 2021, p. 15) and authors' added categories	Details from data
Social	Practices as planned regular routines, occupational tasks	Design meetings, planning, scheduling, designing, building, collaboration, Timber drilling, supervising, reloading, site preparation, quality assessments, maintenance, programming, robot controls
	Episodes as unanticipated or irregular activities	Onsite occurrence of separation of timber drilling activities by human and robot
	Encounters as temporary interactions between two or more individuals	Meetings to consult for design, robot engineers with construction experts, mediators, visionary leaders as drivers
	Roles	Robot engineers, project lead, mediator, project managers, industry experts, contractors, supervisors, workers
	Social relationships	Consultant, mediator, director, supplier, client, sponsor/funder, owner, team member
	Groups	Stakeholders – Builders, contractors, sub-contractors, media, unions, government, designers, strategic management
	Organizations or corporations	SafeWork Australia, Engineering firm, Research Institute, Building and Construction company
	Values and attitudes	Intent, sublimes, mindset, acceptance, resistance, fears, success
Technical	Performance	Robot capabilities, HRT capabilities and limitations
	Collaboration	Enablers, barriers, interactions
	Hardware	Robot, devices, tools
	Software	GUI interface, sensors, mapping and navigation, drilling motions, speed

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Data availability The raw data that support the findings of this study are not openly available due to ethical reasons of participant confidentiality, anonymity, and privacy. Links/citations to publicly available datasets analyzed or generated during the study, and summaries of the data are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at University of Technology Sydney.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Ang KC, Sankaran S, Liu D, Shrestha P (2023) From lab to field: a sociotechnical systems view of the organizational cycle for intelligent robotics technologies ideation, planning, design, development and deployment. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction

Aurecon (2022) Aurecon reimagines mass timber construction with robotics technology. Retrieved 16 June 2022 from https://www.aurecongroup.com/about/latest-news/2022/may/aurecon-robotics-technology-building-360

Barnett W, Foos A, Gruber T, Keeling D, Keeling K, Nasr L (2014) Consumer perceptions of interactive service robots: a value-dominant logic perspective. The 23rd IEEE international symposium on robot and human interactive communication

Berx N, Decré W, Morag I, Chemweno P, Pintelon L (2022) Identification and classification of risk factors for human–robot collaboration from a system-wide perspective. Comput Ind Eng 163:107827

Bessant J, Rush H (1995) Building bridges for innovation: the role of consultants in technology transfer. Res Policy 24(1):97–114

Bock T (2015) The future of construction automation: technological disruption and the upcoming ubiquity of robotics. Automat Construct 59:113–121. https://doi.org/10.1016/j.autcon.2015.07.022

Bock T, Yoshida T (2016) Special issue on construction and built environment. J Robotics Mechatron 28(2):115–115. https://doi.org/10.20965/jrm.2016.p0115

Brenzel K, Jeans D (2019, 4 June 2024). Warped lumber, failed projects: TRD investigates Katerra, SoftBank's $4B construction startup. The Real Deal. https://therealdeal.com/new-york/2019/12/16/softbank-funded-construction-startup-katerra-promised-a-tech-revolution-its-struggling-to-deliver/

Brocal F, Paltrinieri N, González-Gaya C, Sebastián MA, Reniers G (2021) Approach to the selection of strategies for emerging risk management considering uncertainty as the main decision variable in occupational contexts. Saf Sci 134:105041. https://doi.org/10.1016/j.ssci.2020.105041

Bryant A, Charmaz K (2007) The Sage handbook of grounded theory. Sage

Carra G, Argiolas A, Bellissima A, Niccolini M, Ragaglia M (2018) Robotics in the construction industry: State of the art and future opportunities. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction

Castells M (2010) The information age. Media Studies: A Reader 2(7):152

Chang S, Francis Siu M-F, Li H, Luo X (2022) Evolution pathways of robotic technologies and applications in construction. Adv Eng Inform 51:101529. https://doi.org/10.1016/j.aei.2022.101529

Christiernin LG (2017). How to describe interaction with a collaborative robot. Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction

Construction-Robotics (2024) Mule. Construction Robotics. https://www.construction-robotics.com/muleml150/

Creswell JW (2014) Research Design Qualitative, Quantitative and Mixed Methods Approaches 4th Edition (4 ed.). Sage

Cunha A, Ferreira F, Sousa E, Louro L, Vicente P, Monteiro S, Erlhagen W, Bicho E (2020) Towards Collaborative Robots as Intelligent Co-workers in Human-Robot Joint Tasks: what to do and who does it? ISR 2020; 52th International Symposium on Robotics

Delgado JMD, Oyedele L, Ajayi A, Akanbi L, Akinade O, Bilal M, Owolabi H (2019) Robotics and automated systems in construction: understanding industry-specific challenges for adoption. J Build Eng 26:100868

Eisenhardt KM, Graebner ME (2007) Theory building from cases: opportunities and challenges. Acad Manag J 50(1):25–32

Emery FE, Trist EL (1972) Towards a social ecology: contextual appreciation of the future in the present. Plenum Press

FBR (2023). Precision Construction Robot: Hadrian X. Retrieved 4 June 2024 from https://www.fbr.com.au/view/hadrian-x

Flyvbjerg B (2006) Five misunderstandings about case-study research. Qual Inq 12(2):219–245. https://doi.org/10.1177/1077800405284363

Frazier S, Pitts BJ, McComb S (2022) Measuring cognitive workload in automated knowledge work environments: a systematic literature review. Cogn Technol Work 24(4):557–587

Frazier S, McComb SA, Hass Z, Pitts BJ (2024) The moderating effects of task complexity and age on the relationship between automation use and cognitive workload. Int J Hum Comput Interact 40(7):1746–1764. https://doi.org/10.1080/10447318.2022.2151773

Gharbia M, Chang-Richards A, Lu Y, Zhong RY, Li H (2020) Robotic technologies for on-site building construction: a systematic review. J Build Eng 32:101584. https://doi.org/10.1016/j.jobe.2020.101584

Gibbert M, Ruigrok W, Wicki B (2008) What passes as a rigorous case study? Strateg Manag J 29(13):1465–1474

Han IX, Meggers F, Parascho S (2021) Bridging the collectives: a review of collective human–robot construction. Int J Archit Comput 19(4):512–531

Hennink MM, Kaiser BN, Marconi VC (2017) Code saturation versus meaning saturation: how many interviews are enough? Qual Health Res 27(4):591–608

Hennink M, Hutter I, Bailey A (2020) Qualitative research methods. Sage

Hoffman G, Breazeal C (2004) Collaboration in human–robot teams. AIAA 1st intelligent systems technical conference

Hussain S, Sanders EBN, Steinert M (2012) Participatory design with marginalized people in developing countries: Challenges and opportunities experienced in a field study in Cambodia. Int J Des 6(2):91–109

Jipp M (2016) Expertise development with different types of automation: a function of different cognitive abilities. Hum Factors 58(1):92–106

Kant V (2016) Cyber-physical systems as sociotechnical systems: a view towards human–technology interaction. Cyber-Physical Systems 2(1–4):75–109. https://doi.org/10.1080/23335777.2017.1289983

Karakikes M, Nathanael D (2023) The effect of cognitive workload on decision authority assignment in human–robot collaboration. Cogn Technol Work 25(1):31–43

Kim Y, Kim H, Murphy R, Lee S, Ahn CR (2022) Delegation or collaboration: understanding different construction stakeholders' perceptions of robotization. J Manag Eng 38(1):04021084. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000994

Knudsen M, Kaivo-Oja J (2020) Collaborative robots: frontiers of current literature. J Intell Syst: Theory Appl 3(2):13–20

Latour B (2007). Reassembling the social: An introduction to actor-network-theory Oup Oxford

Le DDK, Hu G, Liu D, Khonasty R, Zhao L, Huang S, Shrestha P, Belperio R (2023). The QUENDA-BOT: autonomous robot for screw-fixing installation in timber building construction. 2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)

Liang C-J, Wang X, Kamat VR, Menassa CC (2021) Human–robot collaboration in construction: classification and research trends. J Constr Eng Manag 147(10):03121006

Liang CJ, Le TH, Ham Y, Mantha BRK, Cheng MH, Lin JJ (2024) Ethics of artificial intelligence and robotics in the architecture, engineering, and construction industry. Autom Constr 162:105369. https://doi.org/10.1016/j.autcon.2024.105369

Lofland J, Snow D, Anderson L, Lofland LH (2022) Analyzing social settings: a guide to qualitative observation and analysis. Waveland Press

Lusch RF, Vargo SL (2014) Service-dominant logic: premises, perspectives, possibilities. Cambridge University Press

MBA (2023) *Building and construction is the 'heart and soul' of the Australian economy*. Master Builders Australia. Retrieved 28 February 2024 from https://masterbuilders.com.au/

McKinsey GI (2018) Skill shift: Automation and the future of the workforce

Melenbrink N, Werfel J, Menges A (2020) On-site autonomous construction robots: towards unsupervised building. Automat Construct 119:103312. https://doi.org/10.1016/j.autcon.2020.103312

Müller C, Graf B, Pfeiffer K, Bieller S, Kutzbach N, Röhricht K (2020) World Robotics 2020 –Service Robots. V. S. GmbH

Nasadowski B (2015) Design and social impact: a cross-sectoral agenda for design education research and practice by julie lasky In: Taylor & Francis. Design Culture 7(1):133–135

Norman DA, Stappers PJ (2015) DesignX: complex sociotechnical systems. She Ji: J Design Econ Innovation 1(2):83–106

NSC (2022) Industry details-construction. Commonwealth of Australia. Retrieved 14 June 2022 from https://labourmarketinsights.gov.au/industries/industry-details?industryCode=E

Pan W, Hu R, Linner T, Bock T (2018) A methodological approach to implement on-site construction robotics and automation: a case of Hong Kong. Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC)

Pan M, Pan W (2020) Stakeholder perceptions of the future application of construction robots for buildings in a dialectical system framework. J Manag Eng. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000846

Parker SK, Grote G (2022) Automation, algorithms, and beyond: why work design matters more than ever in a digital world. Appl Psychol 71(4):1171–1204

Pasmore W, Winby S, Mohrman SA, Vanasse R (2019) Reflections: sociotechnical systems design and organization change. J Chang Manag 19(2):67–85

Patton MQ (1990). Qualitative evaluation methods.

Peruzzini M, Grandi F, Pellicciari M (2020) Exploring the potential of Operator 4.0 interface and monitoring. Comput Ind Eng 139:105600. https://doi.org/10.1016/j.cie.2018.12.047

Raffik R, Sathya RR, Vaishali V, Balavedhaa S (2023) Industry 5.0: enhancing human-robot collaboration through collaborative robots–a review. 2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)

Robinson OC (2014) Sampling in interview-based qualitative research: a theoretical and practical guide. Qual Res Psychol 11(1):25–41

Robotics-Australia-Group (2022) A Robotics Roadmap for Australia 2022. R. A. Group. https://roboausnet.com.au/wp-content/uploads/2021/11/Robotics-Roadmap-for-Australia-2022_compressed-1.pdf

Saldaña J (2021) The coding manual for qualitative researchers. The coding manual for qualitative researchers, 1–440.

Schneckenberg D, Velamuri VK, Comberg C, Spieth P (2017) Business model innovation and decision making: uncovering mechanisms for coping with uncertainty. RD Manag 47(3):404–419

Sheridan TB, Nadler ED (2006) A review of human-automation interaction failures and lessons learned. Volpe National Transportation System Center, Cambridge, MA

Siggelkow N (2007) Persuasion with case studies. Acad Manag J 50(1):20–24

Sony M, Naik S (2020) Industry 4.0 integration with socio-technical systems theory: a systematic review and proposed theoretical model. Technol Soc 61:101248. https://doi.org/10.1016/j.techsoc.2020.101248

Sørensen E, Torfing J (2016) Theories of democratic network governance. Springer

Stake RE (1995) The art of case study research. Sage

Stapel J, Mullakkal-Babu FA, Happee R (2019) Automated driving reduces perceived workload, but monitoring causes higher cognitive load than manual driving. Transport Res F: Traffic Psychol Behav 60:590–605

Tay B (2003) *Using action research to develop a social technical expert system for an industrial environment* PhD dissertation. Southern Cross University, Graduate College of Management

Thomas DR (2006) A general inductive approach for analyzing qualitative evaluation data. Am J Eval 27(2):237–246. https://doi.org/10.1177/1098214005283748

Wang Q, Liu D, Carmichael MG, Aldini S, Lin C-T (2022) Computational model of robot trust in human co-worker for physical human-robot collaboration. IEEE Robotics Autom Lett 7(2):3146–3153

Xiao B, Chen C, Yin X (2022) Recent advancements of robotics in construction. Autom Constr 144:104591

Yang Y, Pan M, Pan W (2019) 'Co-evolution through interaction' of innovative building technologies: the case of modular integrated construction and robotics. Automat Construct 107:102932. https://doi.org/10.1016/j.autcon.2019.102932

Yin RK (2009) Case study research: Design and methods. vol. 5. Sage

Yin RK (2014) Case study research design and methods (5 ed.) Sage