From Lab to Field: A Sociotechnical Systems View of the Organizational Cycle for Intelligent Robotics Technologies Ideation, Planning, Design, Development and Deployment

Karyne C.S. Ang[1], Shankar Sankaran[1], Dikai Liu[2] and Pratik Shrestha[3]

[1]School of Built Environment, University of Technology Sydney, Australia
[2]School of Mechanical and Mechatronics Engineering, University of Technology Sydney, Australia
[3]Building Structures, Aurecon Group, Australia
karyne.ang@uts.edu.au, shankar.sankaran@uts.edu.au, dikai.liu@uts.edu.au, Pratik.shrestha@aurecongroup.com

Abstract

Advanced intelligent robotics technologies like autonomous and collaborative robots in construction sites have been explored in the literature for more than a decade. However, there are only a few prototypes that successfully make it to the field due to various reasons. There is burgeoning interest in the design, development and deployment of intelligent robot technologies due to the spread of Industry 4.0.

Ideas for a robot project often stem from a visionary's intention to solve industry challenges such as workplace safety and well-being, productivity, market competitiveness. The translation of the visionary's idea into reality goes through an iterative design and development process before a tangible robot prototype is produced. Within the organisational cycle, the abilities to lead, organise, mediate, plan, communicate and engage are important. At each stage of the cycle, different interactions and considerations are required involving different stakeholders. However, for ultimate success, the proof of concept, acceptance and deployment into field (reality) are equally important aspects of the development for new technologies.

This study examines the sociotechnical systems processes involved in an innovation project about intelligent robot technologies in construction. We examine stakeholder interactions across the system from ideation, planning and design, rapid iterations and prototyping that resulted in a successful development of a proof-of-concept intelligent robot onsite.

Keywords:
socio-technical systems; stakeholders; design-thinking; intelligent robots; construction

1 Introduction

A Socio Technical Systems (STS) perspective is applied to explore how different stakeholders contribute to organise, plan, design and develop to ultimately deploy and work with robots onsite in construction work. This perspective is important because the study demonstrates useful insights into how co-operative work involving humans and intelligent robots could be designed and structured. Within the larger sociotechnical system, stakeholders are both internal and external and could include project owners, mediators, designers, planners and workers, labour unions and media.

1.1 Industry 4.0 and Construction 4.0

Industry 4.0 promoted 'horizontal, vertical and digital integration' of processes used to design produce and deliver products. [1] (p.22). Based on the strategies and impact of Industry 4.0 the construction sector also realised that it could transform itself. To facilitate this transformation Construction 4.0 was conceived 'to overcome the existing horizontal, vertical, and longitudinal fragmentation and to take a holistic approach to the improvements needed in the industry [2] (p. 301). One of the nine pillars of Industry 4.0 is deployment robots which applies to Construction 4.0. Robots in construction

Robots have been used in construction since the 1970's. Their application in construction has increased evidenced by the number of articles appearing in ISARC proceedings on the application of robotics in construction [3]. De Soto & Skibiniewski [3] predict that Construction 4.0 concept 'makes the construction automation and robotics promising' (p. 292) and will lead to an increase in the use robotics in construction. However, the introduction of robots will require 'human-machine relationship to evolve' [3] (p. 302) requiring more attention towards human-robot interaction that incorporates the 'social aspects of human robot collaboration' [4] (p.669).

1.2 Robot and Human Collaborative workspaces

To facilitate collaboration with humans at work, robots used in collaborative work would be designed differently [5]. Factors considered in designing collaborative robots should ensure that they work at lower speeds than industrial robots used in assembly lines; they are designed to cooperate with humans and not replace them; they are safe to work in shared workspaces; and they are easy to program enabling them to be flexible to carry out different tasks [5].

The popular belief that automation will reduce 'human interaction' is untrue as humans will need to develop new skills when new technologies are introduced [6] (p. 10124). Sony and Naik call for adopting a sociotechnical perspective for a successful and sustainable implementation of new technologies [6]. Adopting such a perspective could help in designing robots for use in the construction sector. We now briefly review the sociotechnical aspects of introducing automation in a workplace.

1.3 Sociotechnical systems and design

STS have their origins in the work of the Tavistock Institute Human Relations in the in the UK [7]. Socio-technical theory has at its core 'the idea that the design and performance of any organisational system can only be understood and improved if both 'social' and 'technical' aspects are brought together and treated as interdependent parts of a complex system' [8] (p 464).

One of the earliest scholars to develop some rules to guide sociotechnical systems designs was Cherns [9]. Cherns' principles have been updated for the digital age by Clegg [8] by developing a sociotechnical framework that conceptualises modern work as a complex system comprising of social (people, culture and goals and technical (technology, infrastructure and processes) elements. Recently, Eason [10] has suggested further that four principles are important in designing sociotechnical systems:

1. Implementing using minimum critical specifications with flexibility for adaptation during application to fit local circumstances.
2. Aligning the social and technical aspects of a system to the processes they are to undertake using contextual knowledge.
3. Enabling user participation to understand implicit aspects of the social system from people who will use the system.
4. Preparing for evolution of the solution to be effective.

The last point is reinforced by Pasmore et al. [11] who argue that 'In traditional STS [sociotechnical systems), the goal was to design the social system around a fixed technical system in a way that maximised throughput and quality while satisfying human needs. In the next generation STS, the goal of balanced optimisation is predicated on the notion that everything is in motion' (p. 79). It is further predicted that future organisations introducing changes in their work processes would use design thinking approaches to designing sociotechnical systems [11]. Design thinking 'is a discipline that uses the designer's sensibility and methods to match people's needs with what is technologically feasible and what a viable business strategy can convert into customer value and market opportunity' [12] (p. 85). The design thinking process can be consolidated into five stages – empathise, define, ideate, prototype and test [13] (p. 230). These elements of design thinking are mentioned in numerous STS literature but have not been extensively explored in the construction context.

In sum, STS theory explores how the introduction of new technology in organisations impacts on people, specifically how multi-skilled people work together as self-organised units to optimise social and technical systems [14]. Accordingly, optimal performance requires attendance to both the social and technical aspects of work organisation. Our review of the literature showed that very few cases about intelligent robot technologies in construction are reported.

We draw from the STS worldview to explain how different stakeholders across multiple systems organise, plan, design and develop to ultimately deploy and work with robots in a construction project.

The research questions addressed in this paper are:

1. *How does an innovative idea about intelligent robot technologies translate into practice in the construction industry?*
2. *What roles do various stakeholders play from ideation to deployment in innovation projects in the construction sector?*

The research context is a construction site where an intelligent robot was tested as proof-of-concept in field. Based on a real-life case study of an intelligent robot for automating a construction task we propose further considerations for teams designing collaborative or co-operative working roles, tasks and structures and networks for the construction workplace.

2 Research Methodology

2.1 Data Collection

A single case study was used to explore how ideas about intelligent robot technologies might be translated into practice. Through qualitative semi-structured interviews, the case study drew upon the perspectives of various stakeholders involved in the innovation project. Case studies provide an opportunity to investigate a real-life, contemporary bounded system (a case) over a set time. Detailed, in-depth data involving multiple sources of information were collected and analysed to offer different in-depth perspectives, thick description and triangulation [14]. In this study we gathered stakeholder insights that traces the ideation, design, development and proof-of-concept test in field of an intelligent robot at a building construction worksite.

Publicly available documents from various media sources (news articles, videos, TV reports), confidential organisational 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 organisation where the robot was delivered. Profiles of the four interview participants can be found in Appendix 1, Table 1.

2.2 Data Analysis

The analysis used a systematic cycle with iterative coding and recoding that included categorising, sorting, prioritising, integrating, synthesising, abstracting, conceptualising, and finally, theory building [15]. Throughout this process, we applied an STS lens to address the research questions on how innovative ideas about intelligent robot technologies translate into practice in the construction industry. We considered the various roles that stakeholders played from ideation to deployment in this innovation project. The STS lens applied fits well with the interpretive nature of this study as indicated by Lofland et al [16] whereby social life happens at the intersection of one or more stakeholders (e.g. the interviewees) who engage in one or more activities (e.g., the behaviours in strategy, planning, design, development and deployment) and at a particular time in a specific place e.g., the case study of an intelligent robot project that was ultimately deployed at a construction site. We used Nvivo qualitative analysis software to map, organise and conceptualise the themes into conceptual clusters.

The Intelligent Robot Development team composition at the various stages in the cycle of the prototype development from (1) strategy planning and organisation consists of the Mediator as the project lead in engineering Design, Lead Robotics Director, Construction client, Designers and Construction Building experts and crew; while (2) is the design, development and testing team comprising Robotic engineers, Mechanical (hardware) and software engineers who are led by the Robotics Director and (3) Robot operations and proof-of-concept deployment on site that comprises the Operator of the robot, the Robot itself, Supervisor and Laborer. These clusters as illustrated in Figure 1 (developed for this paper) are marked by number and colored boundaries. External to the team are the secondary stakeholders labelled as (4) comprising the media and labour union. Findings relating to the views of the primary stakeholder groups involved in the innovation project in the stages from (1) to (4) are presented and discussed from an STS perspective in the following section.

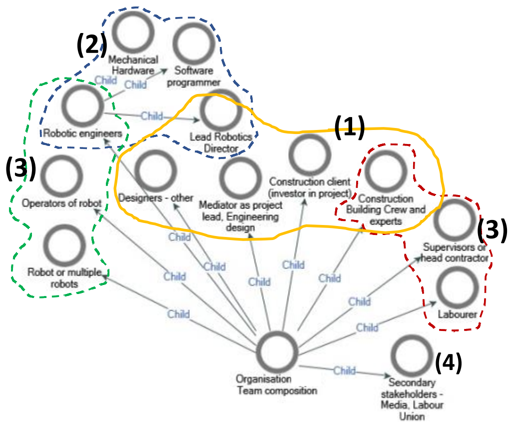

Figure 1. Organisational stakeholders in intelligent robot development from planning and design to deployment (developed for this paper)

2.3 Synopsis of the case study for context

Timber delivers sustainability and environmental benefits, resulting in the increasing popularity for Mass Engineered Timber construction. Building with timber is also faster, quieter and safer, and produces less waste. However, given the repetitiveness of labour-intensive tasks of installing screw fixings in a timber construction site, fatigue and back injury due to prolonged and awkward poses can occur.

In collaboration with MODA (client) and AURORA (construction engineering) and MAXPRO (Building construction firm), researchers at the University of Technology Sydney developed an autonomous robot for a timber building construction, The intelligent robot developed provides an innovative solution to address significant work health and safety issues, while improving efficiency and accuracy of the process.

The intelligent robot comprises of a mobile platform and a robotic arm with six degrees of freedom mounted with a mechanism to perform screw fixings. The robot autonomously navigates and localises itself on a floor at the construction site and makes its way to a section where long screws need to be fixed. Once it reaches the section, the robot calculates the locations of the screws, and moves its robot arm to the desired location while avoiding collisions with the surrounding environment. With advanced control methods the robot installs the screws into the timber floor. Once a section is completed, the robot automatically progresses to the next section to install more screws.

Workers could monitor the operation and view live data through a simple user interface. At the point of prototype deployment onsite, a human operator was needed to feed the screws to the robot as the self-feeding mechanism was not ready due to time constraints. The prototype and human worker feeding the robot is shown in Figure 2.

Figure 2. Intelligent robot prototype with human operator feeding screws

3 Findings and Discussion

3.1 Findings from stakeholders in each stage of the organisational cycle

In this paper, we trace how the initial idea of having robots in construction moved into intention, strategy, organisation, planning, design, development and eventual deployment in the field. The organisational process provides an insight into how an innovation system works to eventuate intelligent robot technologies deployed at the construction site.

When we consider how innovation projects are organised from an STS perspective, there are different networks at play in the project with different levels of stakeholder interactions at different points in time across the lifecycle of the project.

The research data enabled us to examine the STS processes and stakeholder interactions in the system from the start, including ideation to the boardroom, what happened during the design thinking meetings and how the robots were developed, tested and a proof-of-concept deployed on site.

3.1.1 Ideation, consultation and strategic planning

At the beginning, an idea was proposed with the intention of innovatively addressing some of the issues faced while harnessing the opportunities provided in the construction industry. The project leader from AURORA, an engineering construction firm initiated the idea of using robots for timber construction and proposed it to the client (MODA).

The idea and reasoning: "What's *something cool that we can do and embed in research? It was a joke, really. We just said, 'Wouldn't it be funny if we got robots to build part of the building?' And MODA said, 'Yeah, let's make it happen'."* (PRAKA). PRAKA also indicated that the client (MODA) was forward-thinking, and research driven. They were willing to invest in advanced technologies that would enhance the systems in construction while addressing the issues of cost and safety for their workers. The ideation was coupled with strong intentions and rationale for the organisation and industry at large, *"Why not make a wonderful [timber] material readily available, and couple that with automation, and innovation to make it even faster, even cheaper, even better to build. At the moment, timber construction attracts cost premium. The material has more cost premium than concrete and steel does. If we use automation and innovation and robotics to make timber construction even faster to build, we bring the cost price down, which means it becomes more competitive, so that it becomes a material of choice. We disrupt the construction industry. So that was all of the reasoning and rationalisation behind why we needed the robot to do what we needed to do.*"

AURORA acknowledged very early on that they were not robot designers and required the consultation and support of other expert stakeholders. Once the idea was embraced and funds were approved by the client, they immediately sourced and form a multi-disciplinary team of consultants and experts.

Harnessing experts: "we're *not robotic designers, we're not robotics experts. We don't even do robotics…. Soon as day one, the contractor is then on board, we need the robotics team to be on board at the same time…. So we started forming working groups with UTS-IRD Director and the robotics team and as well as MODA. In fact, RMIT was also involved at that time. And we looked at various options. (PRAKA)*

Design thinking and collaboration: *"We use design thinking tools, and all that sort of stuff to hone down into a specific aspect of the timber building*" (PRAKA).

"We had the German supplier, with their product, connections and their manufacturing processes. For the timber design. the lead was asking questions from about 12 other people. The whole team was made up of design managers, or drafting people, project managers, project engineers, all that sort of very technical process." (PEKA)

Integrating social and technical aspects in the system: Integrating the social and technical aspects of the organisational system as done in this case study contributed to the optimal design and performance of the overall project. This approach aligns well with STS concepts whereby these social and technical aspects are brought together upfront and treated as interdependent parts of a complex system [8]. In the early stages of consultation and planning, the project lead introduced, led and mediated the various stakeholders including the client, engineers, contractors and robot designers to collaboratively identify processes, workflows and elements that would differ from a traditional construction system. This was critical as the deployment of intelligent robots onsite would disrupt the existing system of works. This was recognised and the consultation process took note of both the planning for the design of the robots and the design of the systems to facilitate anticipated disruptions to traditional construction work, manage workspaces and schedules, and minimise clashes when incorporating human-robot teams onsite. An STS-based mediation scenario was described by PRAKA, "*We needed the robotics and construction teams, and the engineers at AURORA to sit at the round table and say, This is your traditional form of construction. A contractor will say, here's how I'm going to build everything. Then the robotics team will say, well hang on, where am I going to fit in all this? That discussion to say, Hang on a second, you really need to allow for the robotics seem to come into this, come into that, come into here, and really sort of plan their work from there.*"

The contractor echoes the facilitation and mediation efforts of AURORA, "*PRAKA from AURORA was the most fantastic organiser of a team. The way that he structured the minutes kept people everybody in line. We were paid as consultants [timber experts] to talk about the constructability of the project, the connections and how to get it built to a certain extent. (PEKA)*

We refer to the literature on STS on the need to consider the ecosystem while delivering technological solutions. Pasmore et al. [11] set up a two-day lab called the socio-technical action research lab (STARlab) with a team of diverse experts at Silicon Valley, USA to explore how organisations will evolve taking into considerations social and technical aspects of managing change. The research team predicted that socio-technical design will evolve in the future to optimise technical system design; social systems design; organisation design and ecosystems design. STARlab team also predicted that to manage organisational change will be more inclusive of stakeholders in the ecosystem 'who play important roles in which work systems operates' (p.81). Design labs would bring together diverse stakeholders involved in a change initiative and 'design thinking principles and rapid prototyping' would be applied to move towards viable solutions (p. 81-82). This experience was reflected by one of the interviewees involved in the design thinking workshops.

"I had the pleasure of sitting in three or four design meetings a week with Germany, Italy, and east coast, and the MAXPRO design team. My involvement [in the design thinking sessions] was probably a good six months of knowing that this was gonna happen." (PEKA)

3.1.2 Robot design, development and testing

The second level consists of the technology design, development and testing. Key stakeholders in this system are the Lead Project Engineer as a mediator working very closely with the Robotics team made up of The Director of the Robotics Institution, and the Hardware and Software Robot Engineers.

These stakeholders interacted directly to develop multiple virtual prototypes. Once they were satisfied with the test results, a physical prototype of the intelligent robot was developed, further tested and finally deployed onsite. The approach to experimentation, rapid and iterative prototyping found in new technologies for innovation like Pasmore's STARlab combined with design thinking [11] is described by PRAKA:

Virtual prototype: *"We were able to do a lot of virtual studies for prototyping and failing fast. Rather than building the robot and building 10 of those, we built many in the virtual environment."*

Iterative tests: *"Tested that, it didn't work, tested, it didn't work."*

Physical prototype: *"When we were comfortable with what we wanted, we built a real prototype. And we got some lab testing done."*

Deployment onsite as proof-of-concept: "*Thanks to the whole the testing, we were able to deploy it live on site, which meant that we were able to do it without any issues. Everything was very successful, and we were able to deploy it on site."*

The process of design, development and testing was very iterative. To develop the software programs for the intelligent robot to perform optimally as intended, the software engineer was required to understand the trade nuances of the task of timber drilling and screwing. The robot engineers did not have the initial technical construction expertise and needed to understand this aspect thoroughly before they were able to translate the tasks into hardware and software that made up the robot. To achieve this, the robotics team researched and consulted with expert contractors for industry-specific knowledge and immersed themselves in a hands-on approach to the timber craft of drilling and screwing. This helped them understand the force, torque, angles and alignment of the drills and screws with the boards, appropriate speeds, knowing when to start, stop or adjust the force and ensuring accuracy. This is described by the robotic engineers.

Knowledge transfers and Hands-on immersion: *"They provided us with very specific details about screw sizes, boards that they were using, because we don't know any of that going into the project, we have to get those details slowly."* (GIKA)

"We would buy the tools ourselves, do it ourselves.

He [construction expert] sent us a video, and like a worker I tried to copy it. If we had any issues, we would go to him, 'what are we doing wrong?'" (GIKA)

The robotic engineers also needed to understand the dynamics of construction sites through discussing different scenarios. They were also provided with construction area blueprints and maps by the contractors and construction project engineers.

Scenarios: *"Every single scenario that's possible for a robot drilling machine, you have to think about it, you have to think of it and programming into it"* (PEKA).

Mapping: *"During the design phase, we mapped out different areas for the robot to go to. We worked with the robotics team at UTS"* (PRAKA), and reinforced by GIKA, *"They gave me the floorplan, blueprints, and metadata of the whole structure about the dimensions of everything that they're building. I designed the whole planning and motion algorithms, where the robot has to go, to sense where it needs to drill, and the robot can actually understand its environment before even going there."* (GIKA)

3.1.3 Prototype development and Field trials

Beyond the lab, there was a pragmatic element of 'readiness' coupled by time schedules, client expectations and funding constraints. To ensure that technical tests were not entirely limited to the research lab, once the physical intelligent robot prototype was deemed safe and ready for use, it was deployed as a proof-of-concept in field. An introduction of the intelligent robot onsite changes the overall system. Further social and technical adjustments and improvisations were needed to the construction site, supervision, roles and work allocations needed to be made. For instance,

1. Shared workspaces but separate work sections
2. Human-Robot Teaming requiring collaboration
3. Variation of roles and processes – Robot supervision, quality management and robot operations

1) Shared workspaces but separate sections: Work for the timber workers working on similar tasks as the robot were limited to certain sectioned areas within the shared space with the robot, but not alongside the robot, as evidenced by PEKA, "P*hysically seeing it doing its job, I did see it. I was part of choosing the location where it was going to be done, and what was the practical thing to be done…. we got very limited access to the robot process when it was on site. The interaction was very limited, because it's a very prototype type process. We were told the size of the screw, the location to put it in, and our guys turned up and did it."* (PEKA).

According to the robotic engineer ALKA, one consideration in intelligent robot technologies with collaborative elements is to ensure human safety when allocating tasks," *We can assign this area for human and this area to be done by the robot, or the robot can do it overnight for some tasks."* The separation of work sections in a shared working space can be viewed as complementary in human-robot teaming, and a base level for human-robot collaborative work [17].

2) Human-Robot Teaming depicting collaboration onsite: During deployment in this case study, humans worked with the intelligent robot to operate and control the functions of the robot. In this instance the robotics engineers took the role of the human operator due to time constraints in the project.

"I think they need me and GIKA to show them first of all, how to do that step by step, how we can document it, and maybe [later] they can do it." (ALKA)

The screw-feeding mechanism is still human-operated. as the self-feeding mechanism for the robot was not ready at the point of deployment. *"So now the worker has to load the screws. But later, the robot can ultimately do that"* (ALKA)

"*A human has to feed the robot with the screws, and then the screws can be inserted. The human can immediately move the robot or stop the robot, if it thinks it's in any danger, or it's doing the wrong thing. So that's the human collaboration there right now.*" (GIKA)

These elements of human-robot teaming, in fact, can be considered human-robot collaboration or HRC.

3) Variation of roles and processes: Robot supervision, quality assessment and certifications, robot operations

Workers would need to supervise and operate the robot for monitoring and control, *"We have to check that the robot movements are right. Whether the points that the robot is screwing are okay or not. We [humans] have a good perception, with good eyes, rather than the robot where it just scans the floor. That's the collaboration with robots and the human." (ALKA)*

Installations by the robot, as with a human labourer would need to be quality-certified, "*Part of my quality processes, all our manual installation is checked by an engineer, all of that. So in the robotic component of it would need to be checked by our engineer who's going to sign it off, certified."* (PEKA).

***Robot* operations:** *"So you have something like a computer, just click the button, and the robot will do that for you. They [workers] can learn and adapt, like using other machines in the construction site. Now it looks like another machine, but it's more intelligent."* (ALKA). Designing for the end-users in mind also meant considering how to make it easy for general labourers to operate and work with an intelligent robot, as commented by ALKA: *"From our development and focus, it's whether the interface is good enough for the workers. We try to develop something like look like your phones. And everyone can use that easily."*

3.1.4 External stakeholders (Media, Labour Union)

External stakeholders like the media and construction industry labour union had no direct involvement in the design, planning and deployment. However, they have an interest in the construction innovation and power to influence. They were kept in close communication by the key stakeholders, particularly the client, construction companies and lead project engineer in the process. For instance, the external media interactions for public relations and publicity (e.g., news, videos, social media releases) was managed by AURORA to ensure that publicity was accurately featured as intended to communicate the advances in engineering innovation for the construction sector. The publicised messages addressed worker safety, quality, sustainability and enhancement of worker well-being. The project was also careful to address concerns that such innovations would be threat to job-security. *"That's a huge part of the project is communicating to the team that, in fact, we're not taking away jobs, we're letting the robot do unsafe tasks. There's a big difference between taking away jobs versus eliminating unsafe tasks."* (PRAKA). These external stakeholders were managed as part of the critical larger socio-technical system that interacted with the internal human-robot systems.

3.2 Pulling it all together – Integration, collaboration, mediation and flexibility

Integration and mediation in the project team from an STS perspective is important [18]. The extent of involvement for contractors was communicated and managed upfront by the main lead engineering organisation AURORA, so that contractors are aware that they are tendering for a project that is innovative and therefore should not be viewed as a traditional construction project as revealed by these quotes:

"We put a specific requirement in there for the tenders to respond to say, 'we envisage that we will be doing something innovative, and we'll be using automation and construction, you as the tender need to respond to that and give your commitment'. So all the tenders, the construction companies who responded said, 'We don't know what it is, but we'd love to be engaging in that dialogue'." (PRAKA)

"The first question he asked was, 'We want to engage with you guys, but this project requires innovation, sustainability, and all those sorts of things. Can you help us with ticking those boxes?' (PEKA)

Apart from formal contracts, attributes that contributed to a positive innovation team environment in the construction sector included contractors being forthcoming and collaborative, ability to compromise, willingness to be flexible with the aspiration.

"They were very forthcoming. And very collaborative in the sense that they said, We think we can help you with this. Compromises are important. Whilst we might have had an aspiration to do all of the screw fixings, that was never going to be a reality on this project. So the contractor wouldn't have wanted that because it would have held them up because it's never been done before…. So how do you make it happen? Part of it is collaboration, and part of it is compromise." (PRAKA).

3.3 Research limitations and future research

This study is limited to a single case study in the construction industry. The key stakeholders involved in the design and deployment of an intelligent robot built with the intention of installing timber screws in a large construction site were interviewed, but could be extended to more stakeholders (e.g., workers, external stakeholders). Additionally, researchers were unable to observe workers and the robot on site to examine human-robot teams in action as the building had been completed while this paper was written. This was overcome by videos with information and context for the research. For future research, the following socio-technical systems themes could be studied: human-robot teaming onsite, planning for human-robot teams in construction and multiple systems and levels within the organisational.

4 Implications and Conclusions

Organisations embarking on innovation projects such as intelligent robots in construction and how this is deployed on site as human-robot teams require a clear integration of organisational intention with the views and experiences of different stakeholders in the project from design to deployment. For innovative ideas about intelligent robot technologies to translate into practice in the construction industry, planning and design for workflow processes, roles and task allocations, mapping and zoning, and dynamic workspaces characterised by the construction site are critical in translating a vision into reality.

In practice, this implies that integrating and facilitating sociotechnical aspects of the stakeholders in the system are important considerations when conducting rapid and iterative prototyping and deploying the proof-of-concept onsite. Intelligent robot design, development and deployment onsite require the project lead to harness experts from multiple disciplines in a collaborative design thinking process.

From ideation to deployment, stakeholders hold different roles including leader, mediator, specialist consultant, designer, planner, supervisor, robot operator, expert and learner. Fundamental to the social and cognitive attributes of the various systems stakeholders are a willingness to embrace change (including uncertainty and ambiguity), improvisation, and flexibility. The willingness of various stakeholders in the system to learn, share knowledge, engage in hands-on immersive learning and experimentation can fill the gaps in a socio-technical systems approach in innovations projects. Furthermore, onsite human-robot teaming requires planning from the start including work zones, and task allocations, robot supervision, accountabilities, safety and quality assessment and certifications and robot operations.

In conclusion, through a single case study about mass engineered timber construction, sociotechnical systems processes in an innovation project about intelligent robot technologies in construction were explored. We examined various stakeholder interactions across the system from ideation, planning and design, rapid iterations and prototyping that resulted in a successful deployment of a proof-of-concept intelligent robot onsite. This paper contributes to the application of sociotechnical systems concepts and design thinking in the planning, design, development and deployment of intelligent robots in construction.

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Appendix 1

Table 1 is based on Figure 1.

Table 1 Profiles of case study participants interviewed.

Participant	Role and responsibilities	Stage in the cycle
ALKA	Mechatronics robot engineer (hardware development)	2, 3
GIKA	Senior software robot engineer (programming)	1, 2, 3
PRAKA	Project lead engineer and mediator (overall project)	1, 2, 3, 4
PEKA	Construction consultant (installation of timber components)	1, 3

AURORA (Engineering Construction Firm, MODA (Construction Client), MAXPRO (Building Construction Organisation)