Wang, Z., Mei, Q., Lee, G. Bock, T. & González-Moret, V. (2025). Perceptions of Robotic Inspections for Confined Spaces in Lean Construction: A Qualitative Study. In O. Seppänen, L. Koskela, & K. Murata (Eds.), *Proceedings of the 33rd Annual Conference of the International Group for Lean Construction* (IGLC33) (pp. 987-998)..https://doi.org/10.24928/2025/0137

PERCEPTIONS OF ROBOTIC INSPECTIONS FOR CONFINED SPACES IN LEAN CONSTRUCTION: A QUALITATIVE STUDY

Zhong Wang[1], Qipei Mei[2], Gaang Lee[3], Thomas Bock[4] and Vicente A. González[5]

ABSTRACT

This qualitative study investigates industry professionals' perceptions of robotic inspections for confined spaces within the framework of Lean Construction 4.0 with a focus on facility maintenance. Confined space inspections are crucial for safety and asset integrity but are often associated with risks, inefficiencies, and high costs. Robotic inspections offer a potential solution, aligning with Lean Construction 4.0 principles that integrates lean principles such as eliminating waste, respect for people, along with technology as a means to an end. Through a focus group with ten experienced facility maintenance professionals, the study explored current practices, challenges, expectations, and hesitations regarding robotic inspections. Findings revealed that while participants recognized the potential of robots to enhance safety, accessibility, and data quality, they also expressed concerns about sensor reliability, data security, cost, and integration with existing workflows. These concerns resonate with previously identified barriers to sensor adoption in construction. The study highlights the need for human-centered design, robust and reliable technology, and seamless integration to successfully implement robotic inspections. Future research should focus on addressing these technological and human factors to advance Lean Construction 4.0 goals and realize the full potential of robotic inspections in creating safer, more efficient confined space inspection processes.

KEYWORDS

Lean construction 4.0, Qualitative Study, Robotics, Sensors, Confined Space Inspection

INTRODUCTION

Confined space inspections are critical for ensuring safety and maintaining asset integrity across various industries, including construction, manufacturing, and utilities (Halder & Afsari, 2023). These inspections help to identify defects, deterioration, or hazards within confined spaces, in both building and built environments, such as tunnels, pipelines, storage tanks, and other

1 PhD Student, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Alberta, Canada, zhong15@ualberta.ca, 0000-0002-7113-3439

2 Assistant Professor, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Alberta, Canada, qipei@ualberta.ca, 0000-0003-1409-3562

3 Assistant Professor, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Alberta, Canada, gaang@ualberta.ca, 0000-0002-6341-2585

4 Chair of Building Realization and Robotics, Technical University of Munich, Munich, Germany, bockrobotics@web.de, 0000-0002-1278-7440

5 Professor, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Alberta, Canada, vagonzal@ualberta.ca, 0000-0003-3408-3863

enclosed structures, which can prevent equipment failures, ensure regulatory compliance, protect worker safety, and ultimately extend the facilities' lifespan (Duran et al., 2002; Liu & Kleiner, 2013; Montero et al., 2015). However, these inspections are often characterized by inherent risks, inefficiencies, and high costs due to the challenging nature of accessing and assessing these spaces (Botti et al., 2017). Traditional methods typically involve manual entry by human workers, exposing them to hazards such as hazardous atmospheres, unstable structures, and potential entrapment (Duran et al., 2002). This not only raises safety concerns, but also results in project delays and increased expenses, representing a form of waste in the Lean Construction (Bajjou & Chafi, 2020).

In the context of Lean Construction, inspections are often categorized as a form of 'non-value-adding but necessary' waste. This perspective is rooted in the foundational work of Juran (2017) and Deming (2018a), who heavily influenced the development of the Toyota Production System and the broader Lean philosophy. They emphasized the importance of "doing things right the first time" to eliminate the need for rework and extensive inspections (De Feo, 2017; Deming, 2018b). To this end, inspections themselves do not directly contribute to the asset's function in the customer's eyes (Koskela, 2000). While inspections do not directly contribute to the transformation of materials into the final product (transformation waste) or add value from the customer's perspective (value waste), they are often deemed necessary to ensure quality and safety. However, the ideal Lean approach aims to minimize the need for inspections by building quality into the process itself, reducing variability through methods such as Statistical Process Control, a concept championed by both Juran (2017) and Deming (2018a), and ultimately striving for a defect-free process (Ohno & Bodek, 2019).

In response to these challenges in minimizing the risks and waste introduced by inspections, the construction industry is increasingly turned towards Lean Construction principles to improve efficiency. Initially, Lean Construction played a crucial role by streamlining processes, improving workflow, and fostering a culture of continuous improvement, which helped to minimize variability and enhance quality, thereby reducing the reliance on extensive inspections (Bajjou & Chafi, 2020; Gusmao Brissi et al., 2022; Salem et al., 2006). More recently, the advent of advanced technologies has further augmented these efforts. The integration of technologies such as robotics, sensors, and data analytics are enabling new possibilities for automating tasks, enhancing data collection, and improving decision-making (Gusmao Brissi et al., 2022; McHugh et al., 2022; Pantazis et al., 2022). However, even though Lean Construction 4.0 is a driver for positive change, technology introduction in construction presents pressing challenges (González et al., 2022).

Robotic inspections offer the potential to transform confined space inspections from a traditionally non-value-adding but necessary task into a more efficient, data-driven, and even value-adding process (Gusmao Brissi et al., 2022; Kopsida et al., 2015). Unlike traditional methods, robotic data offers multi-dimensional insights for identifying defects, predicting failures, optimizing maintenance, and improving resource allocation, shifting inspections from reactive problem detection to proactive prevention and enhanced asset management (Alarcón et al., 2022; Cai et al., 2019; Javaid et al., 2021). Moreover, the ability to collect and analyze data consistently and objectively can lead to more accurate assessments and better-informed decisions about resource allocation. In this sense, robotic inspections can shift the focus from a reactive approach of simply identifying existing problems to proactively preventing future issues and optimizing building and built asset performance (Kopsida et al., 2015). This transformation could potentially elevate inspections from a non-value-adding but necessary activity to a strategic, value-adding process that directly contributes to improved asset management, reduced operational costs, and enhanced safety. Evidence of this effectiveness exists, as seen in the case study analysis from Kadir et al. (2018), which showcases how robots enhance Industry 4.0 operations. However in construction, the successful implementation of robots hinges on understanding the perceptions, expectations, and concerns of industry stakeholders (Xiao et al., 2022). Our prior work identified key barriers to sensor adoption in the construction industry, including construction site complexity, data accuracy and durability, data transmission and fusion, level of automation, big data management, and end-user acceptance (Wang et al., 2025). While the theoretical barriers are identified and the potential benefits of sensor and robotic inspections are recognized, a gap exists regarding the specific perceptions and concerns of industry professionals concerning the adoption of this technology.

This study addresses this gap by exploring perceptions of robotic inspections for confined spaces, aiming to answer: (1) What are the current challenges in manual inspections? (2) What expectations and hesitations do professionals have toward robotic solutions? (3) How can these insights inform Lean Construction 4.0 implementation? Through focus group discussions with individuals possessing extensive experience in building management, infrastructure maintenance, and inspections, we investigate the perceived benefits, challenges, and potential barriers to adopting this technology. The findings aim to contribute to a deeper understanding of how robotic inspections can be effectively integrated into existing workflows to enhance safety, efficiency, and decision-making in the context of confined space management, ultimately driving the practical implementation of Lean Construction 4.0 principles in the construction industry. Addressing this gap is significant because it bridges barriers to adoption, enhances safety and efficiency, and advances Lean Construction 4.0's practical and theoretical framework.

RESEARCH METHOD

This study employed a qualitative research approach to explore industry professionals' perceptions of robotic inspections for confined spaces within the framework of Lean Construction 4.0. Qualitative research methods are well-suited for investigating complex phenomena, understanding perspectives, and generating rich, in-depth insights into experiences and beliefs (Castleberry & Nolen, 2018; Patton, 1990). A focus group methodology was chosen to facilitate interactive discussions and elicit diverse viewpoints from participants with relevant expertise (Rabiee, 2004). The focus group is part of the authors' broader research project in designing and developing multi-dimensional robotic inspection approaches, where it identifies and validates user needs to inform system design and development.

PARTICIPANTS

The focus group comprised ten participants (n=10) located in Alberta, Canada. Participants are with a minimum of eight years of experience in building management, infrastructure maintenance, facility management, or built environment inspections. This purposive sampling strategy ensured that participants possessed practical knowledge and experience related to the research topic (Suri, 2011). The participants represented a diverse range of roles within the industry, including two current tradespersons working in maintenance, two foremen, two project managers, two department directors, and two regional portfolio managers. This diversity in roles allowed for a comprehensive exploration of perspectives, from hands-on operational insights to strategic decision-making considerations (Suri, 2011; Tuckett, 2004). Due to ethical considerations and to maintain participant anonymity, further demographic details are not disclosed.

DATA COLLECTION

Data collection was conducted in-person through a semi-structured focus group discussion. The focus group was audio recorded and moderated by the corresponding author, which lasted approximately 120 minutes. The focus group was approved by the University of Alberta Human

Research Ethics Boards (Ethics ID Pro00147080). To mitigate bias and facilitate a positive group dynamic, the moderator encouraged equal participation and redirected dominant voices.

The thematic areas explored in the focus group discussion were derived from a multi-faceted framework incorporating the research objectives, the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003), insights from our prior work on sensor adoption barriers in the construction industry (Wang et al., 2025), and the principles of Lean Construction 4.0 (González et al., 2022). Specifically, the UTAUT model, one of the most well-applied models on technology acceptance analysis, served as a primary lens for shaping the discussion themes. It focuses on performance expectancy, effort expectancy, social influence, and facilitating conditions, which is able to provide meaningful and valuable insights regarding technology acceptance (Khechine et al., 2016). This framework guided the development of four key themes: Workflow, Challenges, Expectations, and Hesitations. These themes were chosen to provide a comprehensive understanding of industry professionals' perceptions of robotic inspections, encompassing their current practices, the difficulties they face, their hopes for the future, and their reservations about this new technology (Venkatesh et al., 2003).

Workflow: This theme aimed to understand the participants' current practices and procedures for confined space inspections. Mapping out the existing workflow was crucial for several reasons. First, it established a baseline for identifying areas where robotic inspections could integrate and improve upon current practice, aligning with both Venkatesh et al. (2003) and the Lean Construction 4.0 principle of waste elimination (González et al., 2022). Second, understanding the workflow helps to contextualize the challenges and expectations expressed by participants (Venkatesh et al., 2003). Finally, it provides a framework for later discussions about potential integration strategies, addressing a key aspect of the "Decision Support Integration (DAp 2)" barrier identified in our previous work.

Challenges: This theme explored the challenges of manual inspections, including accessibility, safety, and contractor management. These challenges relate directly to the UTAUT constructs of performance and effort expectancy (Venkatesh et al., 2003). Understanding these perceived difficulties helps us assess how robotic inspections might offer performance improvements and reduce effort. This aligns with Lean Construction 4.0's principles of respect for people and integrated solutions (González et al., 2022).

Expectations: This theme explored the participants' vision for how robots could be used in inspections, including desired features, capabilities, and anticipated benefits. This aligns with the UTAUT construct of performance expectancy, capturing beliefs about how robots could enhance job performance, efficiency, and data value (Venkatesh et al., 2003). It also connects to Lean Construction 4.0's focus on technology as a tool and builds upon our prior sensor adoption research by exploring expectations for advanced robotic systems (González et al., 2022).

Hesitations: This theme addressed potential barriers to adoption, including concerns about reliability, cost, data security, and job displacement. These concerns are directly linked to the UTAUT constructs of effort expectancy, social influence, and facilitating conditions (Venkatesh et al., 2003). For example, concerns about reliability and cost can influence perceptions of ease of use and the availability of resources to support adoption. Social influence is relevant as it considers how the perceptions of peers and superiors might impact adoption decisions. This theme also draws upon our previous work on sensor adoption barriers, particularly "Sensing Data Accuracy (DAc 1)," "Sensor Durability (DAc 2)," "Big Data Management (DP 2)," and "End User Acceptance (DAp 1)," providing a framework for analyzing participants' concerns through the lens of established barriers. The Lean Construction 4.0 principle of human-centered systems is also critical here, emphasizing the need to address user concerns and ensure that technology adoption is aligned with human needs and capabilities (González et al., 2022).

By structuring the discussion around these themes, informed by the UTAUT framework, our previous research, and Lean Construction 4.0 principles, the study aimed to generate a comprehensive understanding of industry professionals' perceptions regarding robotic inspections for confined spaces. This multi-faceted approach provides valuable insights for researchers, developers, and practitioners seeking to advance the implementation of this technology within a framework that prioritizes both technological advancements and human factors.

DATA ANALYSIS

Thematic analysis of the transcribed focus group data was facilitated by NVivo qualitative data analysis software and followed a structured, iterative coding process, as illustrated in Figure 1. The process, adapted from grounded theory proposed by Bandara et al. (2015), involved three distinct phases: open coding, axial coding, and selective coding.

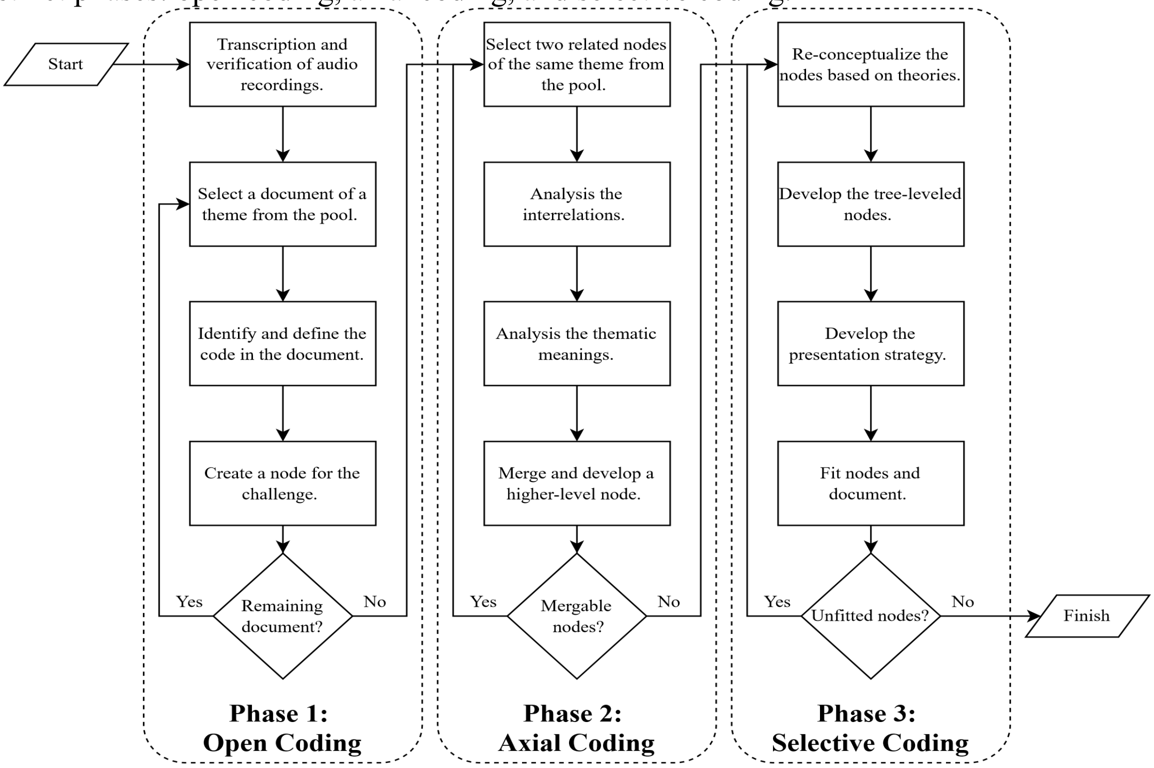

Figure 1: Inductive coding approach using NVivo, adapted from Bandara et al. (2015) and Wang et al. (2025)

In the open coding phase, the transcripts were meticulously reviewed, and meaningful segments of text were identified and assigned initial descriptive codes. This involved a line-by-line analysis to ensure that all relevant concepts and ideas expressed by the participants were captured. Each identified code was clearly defined to ensure consistency and accuracy throughout the coding process. In the axial coding phase, the initial codes were analyzed for interrelationships and connections. Codes that shared common themes or concepts were grouped together and, where appropriate, merged to develop higher-level, more abstract codes. This iterative process involved constantly comparing and contrasting codes to refine their definitions and relationships. Finally, in the selective coding phase, the refined codes were further analyzed and organized around core categories or themes, guided by the theoretical framework of the study, which included UTAUT, our previous work on sensor adoption, and Lean Construction 4.0 principles. This phase involved developing a hierarchical tree-like structure of nodes, representing the main themes and sub-themes that emerged from the data. The final structure was reviewed to ensure that all codes fit within the established themes and that the overall framework accurately represented the data. Throughout the entire process, memos were used to document the analytical decisions, evolving interpretations, and emerging insights, ensuring a transparent and traceable analytical process.

The reliability of the NVivo coding process was prioritized through several steps. First, coders cross-checked initial coding to achieve consistency. Second, inter-coder reliability was established by having two coders independently analyze the same data and resolve discrepancies through consensus. Finally, the coding process was iteratively refined based on team feedback, ensuring a robust and dependable analysis.

DISCUSSION OF FINDINGS

This section presents the findings of the thematic analysis of the focus group data, exploring industry professionals' perceptions of robotic inspections for confined spaces within the framework of Lean Construction 4.0. The findings are organized according to the four main codes that emerged during the analysis: Workflow Tasks, Challenges, Expectations, and Hesitations. Each code is further divided into sub-themes that capture the nuances of the participants' perspectives. A summary of all findings from the qualitative study, including the four main codes in each stage of the workflow, is shown in Figure 2. This section concludes with recommendations for future work that, to the best of the authors' knowledge, have the potential to meet practitioners' expectations and address their hesitations, based on the presented findings.

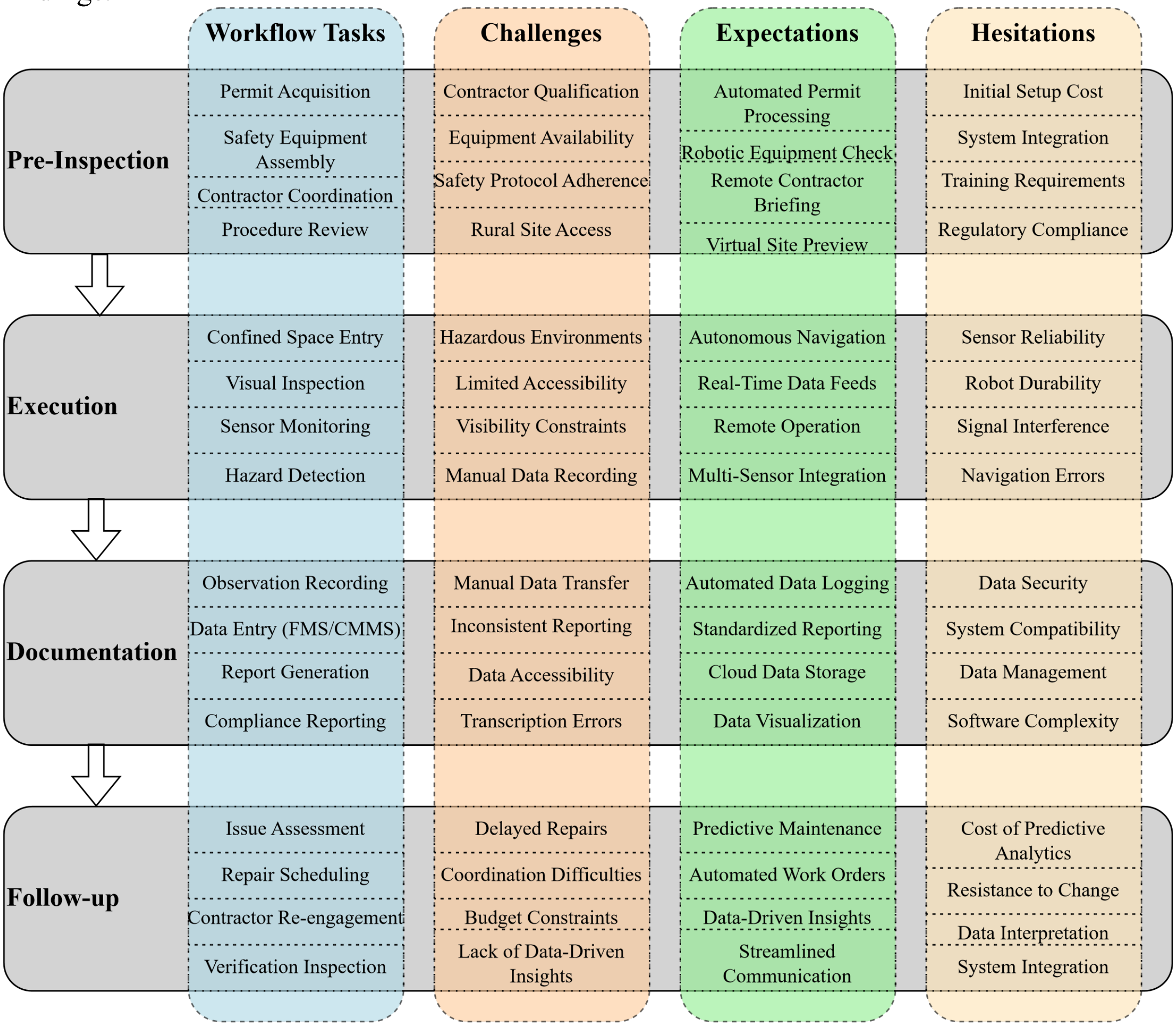

Figure 2: Summary of Findings

CURRENT WORKFLOW TASKS OF CONFINED SPACE INSPECTIONS

The analysis of the "Workflow Tasks" code revealed that current confined space inspection practices are heavily reliant on manual labor, involve extensive paperwork, and adhere to strict safety protocols. Participants described a multi-stage process encompassing preparation, execution, documentation, and follow-up, as summarized in Figure 2.

A significant portion of the current workflow is dedicated to pre-inspection preparation. This includes obtaining necessary permits, assembling and verifying safety equipment (such as fall protection gear, gas sensors, and tripods), and completing mandatory sign-in sheets. The emphasis on safety regulations and the administrative requirements associated with confined space entry were recurring themes. Participants also highlighted the need for specialized equipment and personnel certified to operate in confined environments. This often necessitates the engagement of external contractors, adding another layer of complexity to the workflow.

The execution of inspections typically involves physical entry into the confined space, often requiring the use of safety equipment. Inspections rely heavily on visual observation, aided by flashlights. Participants described the limitations of this approach, particularly in spaces with restricted visibility, such as ceiling voids or areas with numerous obstructions. The reliance on human senses to detect leaks or other anomalies was also identified as a potential limitation, especially when such issues are not readily apparent or occur intermittently.

Documentation procedures involve manually recording observations, gas readings, and any identified issues. Participants indicated the use of facility maintenance systems (FMS) and work order systems to track repairs and manage identified problems. This often involves transferring handwritten notes into digital systems, potentially resulting in errors and inefficiencies.

These findings suggest that current workflows, while prioritizing safety, are often inefficient and time-consuming. They involve numerous non-value-adding activities, such as extensive paperwork, manual data entry, and potentially redundant checks. Aligning with the Lean Construction principle of eliminating waste, this finding highlights a key area where robotic inspections could potentially offer significant improvements.

CHALLENGES OF CONFINED SPACE INSPECTIONS

The "Challenges" code highlighted several key difficulties associated with traditional confined space inspections, primarily related to safety, contractor management, and accessibility. These challenges are summarized in order of response frequency by each stage of workflow in Figure 2.

Participants expressed concerns regarding the maintenance, certification, and availability of safety equipment. Regular inspections and upkeep of equipment like tripods, harnesses, and gas monitors are essential but represent an ongoing operational challenge. The need for specialized rescue equipment and trained personnel in case of emergencies further complicated the process, adding to the logistical and financial burden of inspections. The reliance on external contractors, especially in remote or rural locations, introduced challenges related to ensuring consistent adherence to safety protocols and verifying the quality of work performed. Participants highlighted the difficulty of monitoring contractor activities and ensuring they followed established procedures, particularly when dealing with smaller contractors who might lack robust internal safety systems. Participants emphasized the difficulties of accessing confined spaces, such as ceiling spaces, and the potential hazards encountered during inspections. These include unstable footings, the risk of encountering natural gas leaks, and poor air quality. These factors contribute to the overall risk profile of manual inspections and underscore the need for safer alternatives.

These challenges underscore the need for safer and more efficient inspection methods, aligning with the Lean Construction 4.0 principle of respect for people. The difficulties in managing contractors and ensuring consistent quality also point to the need for more integrated solutions, another core principle of Lean Construction 4.0.

EXPECTATIONS OF ROBOTIC INSPECTIONS

The "Expectations" code revealed a strong desire for robotic solutions that could improve navigation, provide real-time data, operate autonomously, and be adaptable to various inspection scenarios. A summary of expectations of robotic inspection is presented in Figure 2, in order of response frequency.

Participants envisioned robots capable of maneuvering in complex environments. This included the ability to navigate vertical surfaces, climb over obstacles such as conduits, and access tight spaces like ductwork. Enhanced mobility would allow robots to reach areas that are difficult or dangerous for humans to access, directly addressing the accessibility challenges identified in the previous section. Participants expressed a strong preference for robots equipped with sensors capable of providing real-time data streams. This includes live video feeds, sensor readings (temperature, moisture, gas, acoustics), and potentially 3D models or augmented reality overlays. Real-time data access would enable remote inspection monitoring, minimizing physical entry requirements and facilitating rapid issue response. This capability could also decrease reliance on external contractors and ensure adherence to safety regulations. The ability of robots to operate independently for extended periods was highly valued. Participants envisioned robots that could be deployed into a confined space and perform inspections autonomously, reducing the need for constant human control or supervision. Adaptability to different inspection scenarios through features such as interchangeable sensors was also considered crucial.

These expectations align with the Lean Construction 4.0 principle of technology as a means to an end, utilizing robotic capabilities to enhance the inspection process and make it more efficient. The desire for real-time data and remote monitoring also supports the principle of developing human trust in the decision-making process by providing transparent and accessible information, potentially leading to more informed and timely decisions (González et al., 2022).

HESITATIONS ABOUT ROBOTIC INSPECTIONS

The "Hesitations" code revealed concerns about sensor reliability, data security, cost, and potential job displacement, which is shown in Figure 2 in order of response frequency. Participants expressed concerns about the potential for sensors to malfunction or be triggered by innocuous events, leading to false alarms or inaccurate readings. This concern directly relates to the "Sensing Data Accuracy and "Sensor Durability" barriers identified in the previous work on sensor adoption, highlighting the importance of robust and reliable sensor technology for successful robotic implementation (Wang et al., 2025).

Concerns were raised regarding the security of data transmitted and stored by the robots, particularly when using wireless communication or cloud-based platforms. The potential cost of acquiring, implementing, and maintaining robotic inspection systems was also a significant consideration. These concerns align with the "Big Data Management" and "End User Acceptance" barriers identified in the previous research, as well as broader concerns about the financial viability of new technology adoption. Although not explicitly voiced as a primary concern, the desire for affordable and adaptable robots implicitly raised questions about potential job displacement. This relates to the Lean Construction 4.0 principle of human-centered systems, emphasizing the need to consider the impact of technological advancements on the workforce and to ensure that technology is implemented in a way that complements and enhances human capabilities rather than simply replacing them.

The findings demonstrate a complex interplay between the perceived benefits and challenges of robotic inspections, viewed through the lens of Lean Construction 4.0. While participants recognized the potential of robots to enhance safety, improve efficiency, and generate valuable data (supporting long-term benefits and technology as a means to an end), they also expressed concerns about reliability, cost, and the need for seamless integration with existing workflows (highlighting the need for integrated solutions). These findings build upon our previous work on sensor adoption barriers in construction, providing empirical evidence from a specific application context – confined space inspections. The concerns raised by participants regarding sensor reliability, data security, and cost directly map onto the barriers identified in the previous study, such as "Sensing Data Accuracy," "Sensor Durability," "Big Data Management," and "End-User Acceptance." This suggests that these barriers remain relevant and need to be addressed for successful robotic implementation in confined space inspections. The findings also highlight the importance of considering the human element in technology adoption, aligning with the Lean Construction 4.0 principle of human-centered systems.

RECOMMENDATIONS FOR FUTURE WORK

The findings of this study, combined with the principles of Lean Construction 4.0 and insights from previous research on sensor adoption barriers, suggest several promising avenues for future research to advance the implementation of robotic inspections in confined spaces.

1. Sensor Technological Improvement: Addressing technological challenges is paramount. This includes improving sensor reliability and robustness to reduce false triggers and withstand harsh environments, directly addressing the "Sensing Data Accuracy" and "Sensor Durability" barriers identified in our previous work. Further research should also explore secure data transmission and management, utilizing encryption and other security measures to protect sensitive data (Turk et al., 2022), thus addressing the "Big Data Management (DP 2)" barrier and aligning with the Lean principle of fostering trust in decision-making.

2. Acknowledgement of the Human Element: Future research should focus on training programs to equip the workforce with skills to operate and maintain these systems (Khalid et al., 2024), and on investigating optimal human-robot collaboration models. Investigating optimal models for human-robot collaboration in confined space inspections is also crucial. This includes exploring interface designs that facilitate intuitive interaction, defining clear roles and responsibilities, and investigating strategies for fostering trust and effective teamwork between humans and robotic systems (Sheridan, 2016), aligning with the "Requirement of Professional Skills" barrier and the Lean principle of human-centered systems. Furthermore, research is needed on integrating robotic inspections into existing workflows. This involves incorporating data into systems like CMMS or BIM, and adapting processes to leverage robotic capabilities (Javaid et al., 2021; Xiao et al., 2022), addressing the "Decision Support Integration" barrier and the Lean principle of integrated solutions.

3. Value Analysis for Practical Application: comprehensive cost-benefit analyses and field trials are crucial to understanding the return on investment and practical implementation challenges. These analyses should consider both initial and long-term operational costs, as well as the value of enhanced safety and data-driven decision-making, aligning with the Lean principle of long-term benefits. Investigating robotic inspection adoption in other industries facing similar challenges could also offer valuable best practices (Javaid et al., 2021).

By pursuing these research directions, the construction industry can move closer to realizing the full potential of robotic inspections for confined spaces, ultimately advancing the goals of Lean Construction 4.0 and creating safer, more efficient, and data-driven inspection processes.

CONCLUSION

This qualitative study explored industry professionals' perceptions of robotic inspections for confined spaces, framed within Lean Construction 4.0. The findings highlight this technology's potential to enhance safety, improve efficiency, and generate valuable data for decision-making. Participants recognized the benefits of robotic inspections in overcoming limitations of manual inspections, especially regarding accessibility, safety, and data quality, aligning with the core principles of Lean Construction 4.0, including eliminating waste, respect for people, and technology as a means to an end. However, the study also revealed concerns about sensor reliability, data security, implementation cost, and integration with existing workflows, echoing barriers identified in our previous work on sensor adoption, such as "Sensing Data Accuracy", "Sensor Durability", "Big Data Management", and "Decision Support Integration". The findings also emphasize a human-centered approach to technology adoption, aligning with Lean Construction 4.0's human-centered systems principle. These findings not only validate the potential of Lean Construction 4.0 knowledge from a practical perspective, but also extend the understanding of barriers in sensor and robotic adoptions in construction from a theoretical to a practical ground.

While this study provides valuable insights, it is important to acknowledge its limitations. The small sample size (n=10) and the focus on a specific group of professionals within a limited geographical area may limit the generalizability of the findings. Future research should involve larger, more diverse samples. Additionally, the reliance on focus group discussions introduces potential biases. Future studies might use other qualitative or quantitative methods for validation. Despite these limitations, this research contributes to the knowledge on technology adoption in construction, complementing our previous work on sensor adoption barriers. The findings underscore the need for ongoing research, particularly in sensor technology, data security, and human-robot interaction.

Future research should focus on improving sensor reliability, data security, and human-robot interfaces. Cost-benefit analyses and real-world field trials are crucial to demonstrate the value of robotic inspections. Investigating training needs and human-robot teamwork models are also essential for a smooth transition. Applying Lean Construction 4.0's production theory principles, the industry can strategically implement technologies such as robotic inspections, optimizing flow, minimizing variability, and reducing cycle times while enhancing value. This involves viewing construction as a socio-technical production system, and utilizing technology to empower human and improve overall performance. Lean Construction 4.0 offers a roadmap for leveraging technology to achieve core Lean objectives, creating a more efficient, sustainable, and human-centric construction environment. This study's insights can inform implementation strategies aligned with Lean Construction 4.0, contributing to a more sustainable and human-centered approach to construction management.

ACKNOWLEDGEMENTS

The authors would like to express their sincere acknowledgement to the Canada Research Chair Program of the Government of Canada (CRC-2021-00531).

REFERENCES

Alarcón, L. F., Molenaar, K. R., Bastías, A., & Mesa, H. A. (2022). Decision Models to Support the Selection and Implementation of Lean Construction. *Lean Construction 4.0*, 306-322. https://doi.org/https://doi.org/10.1201/9781003150930-19

Bajjou, M. S., & Chafi, A. (2020). Identifying and Managing Critical Waste Factors for Lean Construction Projects. *Engineering Management Journal*, *32*(1), 2-13. https://doi.org/10.1080/10429247.2019.1656479

Bandara, W., Furtmueller, E., Gorbacheva, E., Miskon, S., & Beekhuyzen, J. (2015). Achieving Rigor in Literature Reviews: Insights from Qualitative Data Analysis and Tool-Support. *Communications of the Association for Information systems*, *37*(1), 8. https://doi.org/https://10.17705/1CAIS.03708

Botti, L., Ferrari, E., & Mora, C. (2017). Automated Entry Technologies for Confined Space Work Activities: A Survey. *Journal of Occupational and Environmental Hygiene*, *14*(4), 271-284. https://doi.org/10.1080/15459624.2016.1250003

Cai, S., Ma, Z., Skibniewski, M. J., & Bao, S. (2019). Construction Automation and Robotics for High-Rise Buildings over the Past Decades: A Comprehensive Review. *Advanced Engineering Informatics*, *42*, 100989. https://doi.org/https://doi.org/10.1016/j.aei.2019.100989

Castleberry, A., & Nolen, A. (2018). Thematic Analysis of Qualitative Research Data: Is It as Easy as It Sounds? *Currents in pharmacy teaching and learning*, *10*(6), 807-815. https://doi.org/https://doi.org/10.1016/j.cptl.2018.03.019

De Feo, J. A. (2017). Principles of a Quality Audit Program. In J. A. De Feo (Ed.), *Juran's Quality Handbook: The Complete Guide to Performance Excellence* (7th Edition ed.). McGraw-Hill Education. https://www.accessengineeringlibrary.com/content/book/9781259643613/toc-chapter/chapter9/section/section5

Deming, W. E. (2018a). *Out of the Crisis*. The MIT Press. https://doi.org/10.7551/mitpress/11457.001.0001

Deming, W. E. (2018b). Principles for Transformation of Western Management. In *Out of the Crisis* (pp. 0). The MIT Press. https://doi.org/10.7551/mitpress/11457.003.0006

Duran, O., Althoefer, K., & Seneviratne, L. D. (2002). State of the Art in Sensor Technologies for Sewer Inspection. *IEEE Sensors Journal*, *2*(2), 73-81. https://doi.org/10.1109/JSEN.2002.1000245

González, V. A., Hamzeh, F., Alarcón, L. F., & Khalife, S. (2022). Lean Construction 4.0: Beyond the New Production Management Philosophy. In *Lean Construction 4.0* (pp. 3-14). Routledge. https://doi.org/https://doi.org/10.1201/9781003150930-1

Gusmao Brissi, S., Wong Chong, O., Debs, L., & Zhang, J. (2022). A Review on the Interactions of Robotic Systems and Lean Principles in Offsite Construction. *Engineering, Construction and Architectural Management*, *29*(1), 383-406. https://doi.org/10.1108/ECAM-10-2020-0809

Halder, S., & Afsari, K. (2023). Robots in Inspection and Monitoring of Buildings and Infrastructure: A Systematic Review. *Applied Sciences*, *13*(4), 2304. https://www.mdpi.com/2076-3417/13/4/2304

Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2021). Substantial Capabilities of Robotics in Enhancing Industry 4.0 Implementation. *Cognitive Robotics*, *1*, 58-75. https://doi.org/https://doi.org/10.1016/j.cogr.2021.06.001

Juran, J. M. (2017). *Juran's Quality Handbook: The Complete Guide to Performance Excellence* (7th Edition ed.). McGraw-Hill Education. https://www.accessengineeringlibrary.com/content/book/9781259643613

Kadir, B. A., Broberg, O., & Souza da Conceição, C. (2018). Designing Human-Robot Collaborations in Industry 4.0: Explorative Case Studies. *DS 92: Proceedings of the DESIGN 2018 15th International Design Conference,* https://doi.org/10.21278/idc.2018.0319

Khalid, M., Akanmu, A., Murzi, H., Lee, S. W., Awolusi, I., Manesh, D., & Okonkwo, C. (2024). Industry Perception of the Knowledge and Skills Required to Implement Sensor Data Analytics in Construction. *Journal of Civil Engineering Education*, *150*(1). https://doi.org/https://10.1061/JCEECD.EIENG-1902

Khechine, H., Lakhal, S., & Ndjambou, P. (2016). A Meta-Analysis of the Utaut Model: Eleven Years Later. *Canadian Journal of Administrative Sciences/Revue Canadienne des Sciences de l'Administration*, *33*(2), 138-152. https://doi.org/https://doi.org/10.1002/cjas.1381

Kopsida, M., Ioannis, B., & Vela, P. (2015). A Review of Automated Construction Progress Monitoring and Inspection Methods. *Proceedings of the 32nd CIB W78 Conference on Construction IT,* https://doi.org/10.17863/CAM.92941

Koskela, L. (2000). *An Exploration Towards a Production Theory and Its Application to Construction*. VTT Technical Research Centre of Finland. http://www.gpsustentavel.ufba.br/downloads/lean_construction_koskela_P408.pdf

Liu, Z., & Kleiner, Y. (2013). State of the Art Review of Inspection Technologies for Condition Assessment of Water Pipes. *Measurement*, *46*(1), 1-15. https://doi.org/https://doi.org/10.1016/j.measurement.2012.05.032

McHugh, K., Dave, B., Tezel, A., Koskela, L., & Patel, V. (2022). Towards Lean Construction Site 4.0. In *Lean Construction 4.0* (pp. 17-34). https://doi.org/10.1201/9781003150930-4

Montero, R., Victores, J. G., Martínez, S., Jardón, A., & Balaguer, C. (2015). Past, Present and Future of Robotic Tunnel Inspection. *Automation in Construction*, *59*, 99-112. https://doi.org/https://doi.org/10.1016/j.autcon.2015.02.003

Ohno, T., & Bodek, N. (2019). Genealogy of the Toyota Production System. In *Toyota Production System* (1 ed., pp. 75-92). Productivity Press. https://www.taylorfrancis.com/books/9781000056495/chapters/10.4324/9780429273018-4

Pantazis, E., Koc, E., & Soibelman, L. (2022). The Implications of the 4.0 Revolution in the Aec Industry on the Lean Construction Paradigm: Identifying the Status Quo and Drawing the Path Forward. In *Lean Construction 4.0* (pp. 35-49). Routledge. https://doi.org/https://doi.org/10.1201/9781003150930-3

Patton, M. Q. (1990). *Qualitative Evaluation and Research Methods*. SAGE Publications, inc.

Rabiee, F. (2004). Focus-Group Interview and Data Analysis. *Proceedings of the Nutrition Society*, *63*(4), 655-660. https://doi.org/10.1079/PNS2004399

Salem, O., Solomon, J., Genaidy, A., & Minkarah, I. (2006). Lean Construction: From Theory to Implementation. *Journal of management in engineering*, *22*(4), 168-175. https://doi.org/https://doi.org/10.1061/(ASCE)0742-597X(2006)22:4(168)

Sheridan, T. B. (2016). Human–Robot Interaction: Status and Challenges. *Human Factors*, *58*(4), 525-532. https://doi.org/10.1177/0018720816644364

Suri, H. (2011). Purposeful Sampling in Qualitative Research Synthesis. *Qualitative Research Journal*, *11*(2), 63-75. https://doi.org/10.3316/QRJ1102063

Tuckett, A. G. (2004). Qualitative Research Sampling: The Very Real Complexities. *Nurse researcher*, *12*(1), 47-61. https://doi.org/10.7748/nr2004.07.12.1.47.c5930

Turk, Ž., García de Soto, B., Mantha, B. R. K., Maciel, A., & Georgescu, A. (2022). A Systemic Framework for Addressing Cybersecurity in Construction. *Automation in Construction*, *133*, Article 103988. https://doi.org/10.1016/j.autcon.2021.103988

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User Acceptance of Information Technology: Toward a Unified View. *MIS Quarterly*, *27*(3), 425-478. https://doi.org/10.2307/30036540

Wang, Z., González, V. A., Mei, Q., & Lee, G. (2025). Sensor Adoption in the Construction Industry: Barriers, Opportunities, and Strategies. *Automation in Construction*, *170*, 105937. https://doi.org/https://doi.org/10.1016/j.autcon.2024.105937

Xiao, B., Chen, C., & Yin, X. (2022). Recent Advancements of Robotics in Construction. *Automation in Construction*, *144*, 104591. . https://doi.org/https://doi.org/10.1016/j.autcon.2022.104591