Human-centered design and development framework for autonomous inspection robot systems in Lean Construction 4.0

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Abstract

Purpose – The construction industry is undergoing a transformation driven by the need to optimize workflow, maximize value and eliminate waste – principles outlined in the transformation-flow-value (TFV) model, widely regarded as the theoretical cornerstone of Lean Construction. Lean Construction 4.0 builds upon these principles by integrating advanced technologies and digitalization to create a more efficient, responsive and human-centered construction process. Within this context, autonomous inspection robot systems hold immense potential to transform the construction industry by automating essential tasks that are often hazardous and non-value-adding.

Design/methodology/approach – This paper introduces a human-centered design framework for autonomous inspection robot systems, which is validated through a case study, addressing the need for human-centered design, value-driven development, adaptability and information flow management in robot-driven system development.

Findings – A case study demonstrates the framework's application, showing that the robot inspection system significantly improved usability, enhanced information flow efficiency, minimized human involvement in hazardous inspection tasks and increased value generation.

Originality/value – The framework integrates principles of human-centered design, lean startup methodology and agile development, guiding developers through four distinct phases: empathize and define, ideate and prototype, develop and deploy and monitor and improve.

Keywords Innovation, Technology, Construction, Case study, Information and communication technology (ICT) applications

Paper type Research article

1. Introduction

The construction industry is undergoing a profound transformation, driven by the recognition that optimizing production processes is crucial for maximizing value (Gusmao Brissi *et al*., 2022). This shift is fueled by a growing understanding that the true value of a construction project lies not only in the final built product, but also in the efficiency, sustainability, and human-centricity of the process to achieve it (Gonzalez *et al*., 2022). This realization has brought theories such as the Transformation-Flow-Value Generation (TFV) to the forefront, establishing it as the theoretical foundation of Lean Construction and a guiding framework for

this new era of construction (Salvatierra-Garrido and Pasquire, 2011; Koskela, 2000; Koskela *et al.*, 2007).

The TFV model posits that value is generated not merely by transforming inputs into outputs, but by optimizing the flow of materials, information, and resources throughout the entire construction process (Koskela *et al.*, 2007). It encourages a holistic view of the project, recognizing the interconnectedness of various activities and the importance of streamlining the flow to eliminate waste and enhance efficiency (Salvatierra-Garrido and Pasquire, 2011; Koskela *et al.*, 2007). In that regard, Lean Construction emphasizes the elimination of non-value-adding activities and the continuous improvement of workflows (Gao and Low, 2014). It promotes a culture of collaboration, learning, and respect for people, fostering an environment where every participant in the construction process is empowered to contribute to optimizing flow and maximizing value (Gao and Low, 2014; Sacks *et al.*, 2009).

These theoretical reflections laid the groundwork for the emergence of Lean Construction 4.0, a paradigm that takes these principles to the next level by integrating advanced technologies and digitalization (González *et al.*, 2022). Lean Construction 4.0 envisions a future where the construction process is not only lean and efficient but also highly responsive and adaptable to change (González *et al.*, 2022). It promotes the use of technologies such as Building Information Modeling (BIM), digital twins, Internet of Things (IoT) sensors, and artificial intelligence to enhance collaboration, optimize resource allocation, and improve decision-making throughout the project lifecycle (Arroyo *et al.*, 2022; Herrera and Alarcón, 2022; Pantazis *et al.*, 2022; McHugh *et al.*, 2022).

Lean Construction 4.0 is not only about adopting new technologies; it is about transforming the culture of the construction industry. It emphasizes human-centricity, recognizing that technology should serve to empower construction professionals, not replace them (González *et al.*, 2022). It promotes a data-driven approach, where decisions are based on real-time information and insights gleaned from the wealth of data generated by advanced systems (McHugh *et al.*, 2022; Alarcón *et al.*, 2022). Moreover, it fosters an organizational environment of continuous improvement, where feedback is actively sought and used to refine processes and enhance project outcomes (Herrera and Alarcón, 2022; Alarcón *et al.*, 2022).

Within this context, robot-based systems hold immense potential to transform construction processes, specifically, by automating tasks essential for safety and quality—such as inspections—that do not directly contribute to the final built product (Gusmao Brissi *et al.*, 2022; Xiao *et al.*, 2022; Halder and Afsari, 2023). Traditional inspection is commonly categorized as 'non-value-adding but necessary task' (Koskela, 2000). It often involves manual entry into confined or hazardous spaces, posing risks to human workers and incurring high costs (Halder and Afsari, 2023; Montero *et al.*, 2015/11; Liu and Kleiner, 2013). On the other hand, robot-based systems equipped with advanced sensors and cameras offer a safer and more efficient alternative. These robots can access hard-to-reach areas, perform repetitive inspections with precision, and generate comprehensive reports, freeing up human workers to focus on tasks that require creativity, problem-solving, and decision-making (Halder and Afsari, 2023; Liang *et al.*, 2023). By automating these essential yet non-value-adding tasks, robot-based systems can significantly enhance efficiency, reduce costs, and improve overall project outcomes (Halder and Afsari, 2023).

Human Centered Design (HCD) is a critical philosophy for developing effective robotic systems (Pizzagalli *et al.*, 2021). At its core, HCD is an iterative process that places the needs, wants, and limitations of the end-users at the center of the design and development lifecycle (Abras *et al.*, 2004). This approach involves a continuous cycle of understanding user needs through research, designing potential solutions, prototyping these solutions, and then rigorously evaluating their effectiveness with feedback from the intended users (Dopp *et al.*, 2019). By focusing on the user throughout this process, designers can create robotic systems that are not only functional but also intuitive, accessible, and ultimately satisfying to use (Lowdermilk, 2013). The stages of HCD typically include research to analyze user requirements, concept development to generate initial ideas, detailed design involving

prototyping and usability testing, implementation of the final design, and post-launch evaluation for continuous improvement (Medhi, 2007; Vredenburg *et al.*, 2002; Mao *et al.*, 2005). A cornerstone of user-centric design is the involvement of users in every stage of the design and development process (Abras *et al.*, 2004). This active participation ensures that the robotic system directly addresses the real-world needs and constraints of the confined space inspectors who will be using it (Mao *et al.*, 2005). By working closely with stakeholders, designers can gain valuable insights into the specific challenges, workflows, and environmental factors that are critical for successful implementation (Vredenburg *et al.*, 2002). Gathering user feedback early and often in the process allows for the identification and resolution of potential usability issues, ultimately leading to greater user acceptance and a more effective robotic solution (Vredenburg *et al.*, 2002).

Grounded on the Lean Construction 4.0 theoretical principles and guided by HCD principles, this paper introduces a human-centered design and development framework for autonomous inspection robot systems in the construction industry. The framework integrates HCD, Lean Startup methodology, and Agile Development, guiding developers through Empathize and Define, Ideate and Prototype, Develop and Deploy, and Monitor and Improve phases. A case study demonstrates the framework's application, showing improved usability, enhanced information flow efficiency, minimized human involvement in hazardous tasks, and increased value generation. The framework aims to promote continuous improvement and human-centered technology adoption in the construction industry.

2. Literature review

While lean robotics is well-studied in manufacturing, there is a pressing need for large-scale research on its potential in construction. Gusmao Brissi *et al.* (2022) believe that there is a trend of integrating robotic systems to improve productivity in the construction industry. They explore the interactions of robotic systems and lean construction in the context of offsite construction. Their systematic literature review identifies journal papers addressing the interactions of automation and lean in offsite construction, with a focus on robotic systems. Their work highlights that the AEC industry has been experiencing low levels of productivity, even with the gradual introduction of several new technologies and processes. They also indicate that the integrated adoption of offsite construction, construction automation and lean construction are effective to tackle the factors that are hindering the AEC industry progress. The literature review indicates a notable lack of research on robotic systems within lean construction, suggesting that the AEC industry could greatly benefit from adopting lessons learned in manufacturing.

In the manufacturing industry, lean robotic systems have been applied in the trend of Industry 4.0 for many years. Over a decade ago, Hedelind and Jackson (2011) explore how to improve the use of industrial robots in lean manufacturing systems by comparing Swedish and Japanese manufacturing industries. Their study also proposes some key areas where development could lead to better integration of industrial robotics into lean manufacturing systems. The authors highlight that the primary concept of lean production is the elimination of waste, while the ultimate goal is value creation. However, they also indicate that within industry at that time, studies at Western manufacturing companies show that companies tend not to have any real strategy when investing and applying automation, and many decisions are made on an ad hoc basis.

To improve the level of automation while emphasizing on human empowerment, Malik and Bilberg (2017) address the concept of hybrid automation in assembly systems, utilizing the combination of humans and robots. They present a systematic framework for the deployment of collaborative robots (cobots) in existing assembly cells for enhanced productivity. This framework is based on Roozenburg's engineering design cycle. They highlight that the increasing demand for customization and shortened product life cycles are pushing manufacturers to develop variant-oriented production systems. They also indicate that

flexibility and changeability are key elements in tackling the challenges of a global market. However, the research is limited to addressing production problems in assembly systems, lacking comprehensive consideration of human centricity which is one of the core aspects in human empowerment (Cooley, 2000).

To address this limitation, Colim *et al.* (2021) explore the integration of Lean Manufacturing and Ergonomics and Human Factors with Human-Robot Collaboration. They analyze an industrial implementation of a collaborative robotic workstation for assembly tasks performed by workers with musculoskeletal complaints. Their study demonstrates that the hybrid workstation achieved a reduction of production times, an improvement of ergonomic conditions, and an enhancement of workers' wellbeing. The authors highlight that Ergonomics and Human Factors are still underrepresented in the Industry 4.0 research topic by that time.

With the growing research interests in Socio-Technical Systems, Vlachos *et al.* (2023) explore the integration of Industry 4.0 technologies within lean manufacturing systems, focusing on autonomous guided vehicles and IoTs. They address the challenge of implementing Industry 4.0 technologies in existing lean manufacturing operations and develop an action plan to achieve lean automation. Their research highlights the necessity for a plan to incorporate new technologies from Industry 4.0 into lean manufacturing systems. They also emphasize that socio-technical systems theory is suitable to understand the complexities derived by merging the two distinct domains (lean manufacturing, Industry 4.0) in the absence of a common language.

These studies have explored the development of frameworks for robot-based systems in various scenarios. In the manufacturing industry, while existing research touches on aspects of lean automation, human-robot collaboration, and the role of Industry 4.0 technologies, a holistic framework that combines these elements is lacking. In the construction industry, Lean Construction 4.0 is emerging to provide theoretical guidance for designing socio-technical systems. It prioritizes human-centricity, ensuring technology empowers rather than replaces professionals (González *et al.*, 2022), promotes data-driven decision-making based on real-time insights from advanced systems (McHugh *et al.*, 2022; Alarcón *et al.*, 2022), and fosters a culture of continuous improvement through active feedback to refine processes and improve project outcomes (Herrera and Alarcón, 2022; Alarcón *et al.*, 2022). However, based on the lessons learned from the related research and the pilot studies of Lean Construction 4.0, a crucial research gap can be identified: the lack of a comprehensive framework that effectively integrates human-centered design, value-driven development, adaptability, and information flow management in the development of robot-based systems. The identified gap underscores the need for a comprehensive approach to designing and implementing robot-based systems that are not only efficient and technologically advanced but also user-centered, adaptable, and capable of effectively managing information flow.

3. Research design

The identified research gap highlights the need for a human-centered design framework that effectively guides the development of autonomous inspection robots for Lean Construction 4.0 in terms of human- centricity, data-driven decision-making, and continuous improvement. This framework should address the challenges of human-robot collaboration, value-driven development, system adaptability, and information flow management. To address this gap, this research aims to answer the following research questions:

RQ1. How can a human-centered design framework be developed to guide the development of autonomous inspection robots for Lean Construction 4.0 in terms of human- centricity, data-driven decision-making, and continuous improvement, and how can this framework effectively integrate the theoretical principles of Lean Construction 4.0 to address the challenges of robot-based system development in construction?

RQ2. How can this framework be applied in a real-world scenario to demonstrate its effectiveness in developing and implementing autonomous inspection robotic systems?

To answer these questions, this research adopts the Design Science Research (DSR) methodology. DSR is a problem-solving paradigm that seeks to create and evaluate innovative artifacts to address real-world challenges (Vom Brocke *et al.*, 2020). It is characterized by an iterative process of building, evaluating, and refining artifacts to generate knowledge and contribute to both theory and practice (Gregor and Hevner, 2013). DSR is particularly well-suited for this research as it aligns with the goal of developing and validating a practical framework for designing and implementing robot-based systems in construction (Venable *et al.*, 2017).

The DSR process, as applied in this research, involves three main stages:

Proposing the Framework: The first stage involves developing a comprehensive framework that addresses the identified research gap. This stage will involve integrating the theoretical principles of Lean Construction 4.0 into a cohesive framework that addresses the multifaceted nature of robot-based system development, specifically in terms of human-centricity, data-driven decision-making, and continuous improvement. This integration will ensure that the framework not only guides the technical development of the system but also considers the human factors, information flow, and value generation aspects, promoting a holistic and user-centered approach to technology adoption in construction.

Raising the Hypothesis: The second stage involves formulating null hypothesis, based on the proposed framework. The hypothesis will posit that the application of this framework will lead to the successful development and implementation of autonomous inspection robots that meet the needs of Lean Construction 4.0.

Testing the Hypothesis: The third stage involves an attempt to reject the null hypothesis through a case study. The case study will demonstrate the application of the framework in a real-world scenario, documenting the development process, the challenges encountered, and the outcomes achieved. The results of the case study will be analyzed to evaluate the effectiveness of the framework in addressing the research gap and achieving the objectives of Lean Construction 4.0.

DSR is chosen for this research because it provides a rigorous and structured approach for developing and evaluating innovative solutions to real-world problems (Vom Brocke *et al.*, 2020). The iterative nature of DSR allows for continuous refinement and improvement of the framework based on feedback and evaluation results (Vom Brocke *et al.*, 2020). Moreover, DSR's emphasis on both theory and practice aligns with the goal of this research to contribute to the body of knowledge in Lean Construction 4.0 while also providing practical guidance for industry practitioners.

4. Human-centered design framework
As shown in Figure 1, this framework translates the principles of Lean Construction 4.0 into a tangible, actionable framework for developing robot-based systems. It provides a structured yet iterative pathway, guiding developers through four distinct phases, each with its own set of processes and a key decision point that ensures alignment with user needs and lean principles.

4.1 Empathize and define (S1.1 – S1.3, I 1.1 – I1.3)
The Empathize and Define phase serves as the foundation of the proposed framework, anchoring the entire process in the principles of design thinking and human-centered design. This phase recognizes that technology in construction should not exist in isolation but must seamlessly integrate with the human experience, which is one of the core principles of human-centered design (Cooley, 2000). This phase also incorporates design thinking which prioritizes deep empathy for the end-users, understanding their needs, motivations, and challenges to
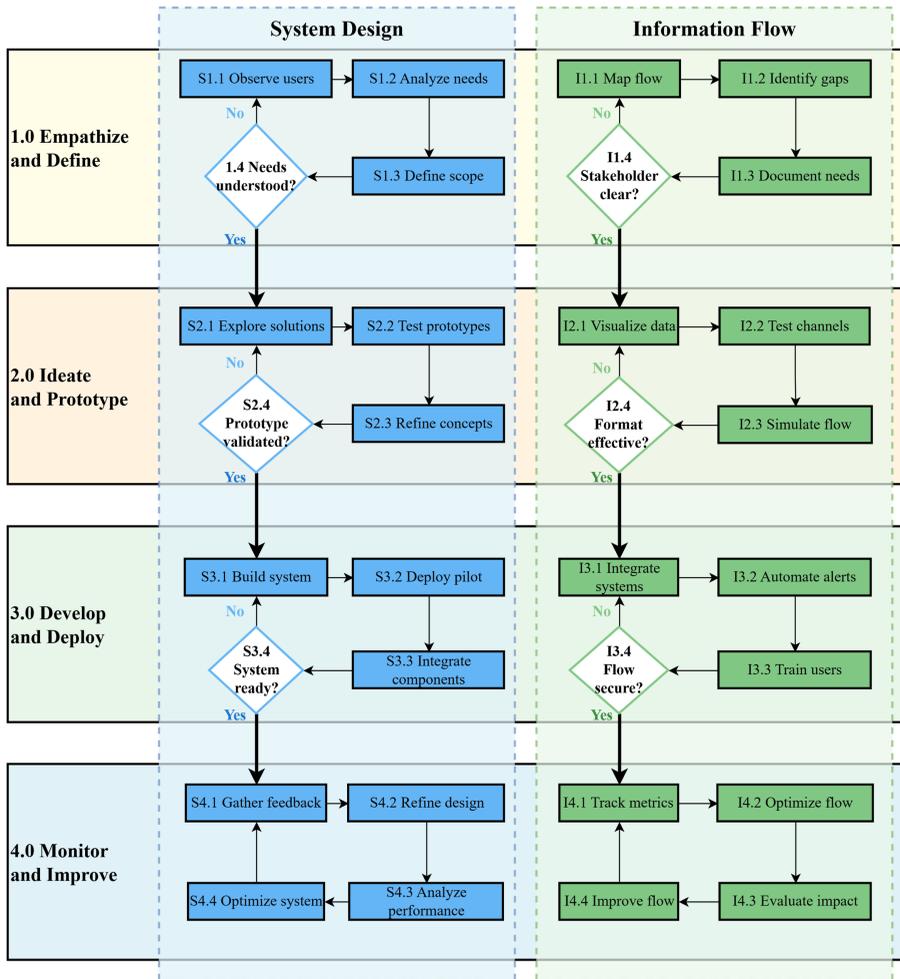
Figure 1. Human-centered design and development framework of autonomous inspection robot-based system for lean construction 4.0

ensure that technology serves as an enabler, not a hindrance (Brown, 2008). By applying these principles, the framework is designed to ensure that the development of robot-based systems is driven by a profound understanding of the construction professionals who will ultimately interact with and benefit from these technologies. This user-centric approach aligns with the core values of Lean Construction 4.0, which emphasizes human trust and long-term benefits in technology adoption.

Through observation (S1.1), insights are gained into the realities of construction professionals: their workflows, pain points, and current technology integration. This observational data is then analyzed (S1.2) to extract meaningful patterns about user needs, preferences, and challenges related to technology adoption and information flow.

Simultaneously, the proposed framework addresses information flow. Construction projects heavily rely on the smooth movement of both physical resources and information (Salvatierra-Garrido and Pasquire, 2011; Gao and Low, 2014; Sacks *et al.*, 2009). Mapping the existing information flow (I1.1) provides a comprehensive understanding of how information

is currently shared and utilized within the project, identifying key stakeholders, their roles, and information needs (Koskela *et al.*, 2007). Analysis of this flow (I1.2) pinpoints bottlenecks, inefficiencies, or areas where information is lost or delayed. These insights are documented (I1.3) to provide a clear picture of the current state of information management.

The completion of this phase lies in clearly defining the scope of the robot-based system (S1.3). This involves articulating the system's objectives, outlining its intended functionalities, and identifying its target users. By the end of this phase, a solid foundation of understanding of user needs should be established.

The effectiveness of this phase is evaluated through various methods to determine if the key decision question can be answered affirmatively. Qualitative study methods, including user surveys and interviews, provide feedback on the clarity and completeness of user stories and information needs documentation (Patton, 1990). Observations in duration of these methods can be supplemented with photographs, videos, and field notes. The analysis of user needs and information flow should be further validated through workshops and focus group discussions with stakeholders.

In addition to these qualitative methods, low-fidelity model-based analysis can provide valuable insights. Use Case Modeling describes system functionality through user interactions (use cases) to identify potential gaps or inconsistencies in requirements (Bittner and Spence, 2003). Data Flow Diagrams visualize the flow of data within the system to ensure that all data elements and processing steps are captured in the requirements (Li and Chen, 2009). These models provide a tangible representation of the system and its intended behavior, facilitating communication and validation among stakeholders.

The key decision in this phase is: Are the needs of the users and the information flow requirements fully understood and approved by the users? This decision, supported by the evaluation results, determines whether the development process can proceed to the next phase, where the focus shifts to generating and evaluating potential solutions.

4.2 Ideate and prototype

The Ideate and Prototype phase channels the essence of the Lean Startup methodology, a powerful approach for navigating the uncertainties of product development. Lean Startup, born from the world of tech startups, emphasizes a "build-measure-learn" feedback loop that prioritizes rapid experimentation, validated learning, and continuous iteration (Ávalos *et al.*, 2019). This philosophy encourages a shift away from elaborate planning and towards a more agile, responsive approach where assumptions are tested, feedback is gathered, and the product evolves based on real-world insights (Zorzetti *et al.*, 2022; Al-Saqqa *et al.*, 2020; Müller and Thoring, 2012). By embracing the Lean Startup principles, the proposed framework ensures that the development of robot-based systems is not a rigid, linear process but a dynamic journey of discovery, adaptation, and continuous improvement.

In this spirit of exploration, the Ideate and Prototype phase encourages the exploration of a wide range of potential solutions (S2.1). This involves brainstorming sessions, technology scouting, and creative thinking to identify the most promising approaches for the robot-based system (Brown, 2008; Zorzetti *et al.*, 2022). Factors such as cost, feasibility, technical limitations, and user preferences should all be carefully considered. The goal is not to find the "perfect" solution right away, but to generate a diverse set of options that can be tested and refined.

Prototyping (S2.2) takes center stage in this phase. Prototypes, whether they are rough sketches, interactive mockups, or functional simulations, provide a tangible representation of the system's envisioned capabilities (Al-Saqqa *et al.*, 2020). These prototypes are not meant to be perfect, but rather to serve as tools for learning and refinement (Al-Saqqa *et al.*, 2020). By putting prototypes in the hands of users, the development team can quickly gather invaluable feedback on their usability, effectiveness, and alignment with user needs (Al-Saqqa *et al.*, 2020). This feedback then informs the refinement of the concepts (S2.3), ensuring that the system evolves in a direction that truly serves the needs of construction professionals.

For the information flow aspect, the focus remains on experimentation and validation. Visualizing data (I2.1) involves exploring different ways to present the information collected by the robot-based system. This could include charts, graphs, dashboards, or even extended reality overlays that provide real-time insights (Khan and Khan, 2011). Testing channels (I2.2) involves evaluating different communication methods, such as email alerts, mobile notifications, or collaborative platforms, to determine the most effective ways to disseminate information to stakeholders (Xu *et al*., 2010). Simulating the flow (I2.3) allows for the identification of potential bottlenecks or delays in the information flow, enabling proactive optimization before full-scale implementation (Khan and Khan, 2011; Xu *et al*., 2010; Chen *et al*., 2008).

The effectiveness of this phase is evaluated through a combination of user-centered and technical methods to determine if the key decision question can be answered affirmatively. First of all, A/B testing allows for a data-driven approach to design decisions. By creating multiple slightly variant versions of a prototype and tracking user interactions, the most effective design among all versions of prototypes can be identified (King *et al*., 2017). Then, usability testing should be applied to provide valuable insights into the user experience, highlighting pain points and areas for improvement (Dumas and Redish, 1993). For these testing methods, analytics tracking should be applied, which offers a broader view of user behavior, revealing how users navigate and interact with information (Dumas and Redish, 1993; Beasley, 2013). For example, visual heatmaps and session recordings provide a deeper understanding of user engagement, highlighting areas of interest and potential confusion (Kukula *et al*., 2010). This process can provide more insightful results when they are monitored by biometric sensors, including Eye-Tracking Sensors, Electroencephalography (EEG) Sensors, Galvanic Skin Response (GSR) Sensors, among others (Kukula *et al*., 2010). These methods, when combined, offer a comprehensive evaluation of the prototype's effectiveness and its alignment with user needs and information flow requirements.

The key decision in this phase is: Does the prototype meet user needs and information flow requirements? This decision, supported by the evaluation results, determines whether the development process can proceed to the next phase, where the focus shifts to building and deploying the system.

4.3 Develop and deploy (S3.1 - S3.3, I3.1 - I3.3)

This phase, deeply rooted in the tenets of Agile Development, marks the transition from conceptualization to realization. Agile Development, with its emphasis on iterative progress, collaboration, and responsiveness to change, provides the guiding principles for bringing the envisioned robot-based system to life (Al-Saqqa *et al*., 2020; Shore and Warden, 2021). This approach acknowledges the dynamic nature of the construction environment and the need for a development process that can adapt to evolving needs and feedback (Al-Saqqa *et al*., 2020). By adhering to Agile principles, the proposed framework ensures that the system is not only built efficiently but also remains flexible and responsive throughout its lifecycle. This aligns with the core values of Lean Construction 4.0, which emphasizes the integration of technology and human-centricity in construction processes.

The development process (S3.1) involves breaking down the system into smaller, manageable modules, prioritizing those that deliver the most value to users. This modular approach allows for incremental development, testing, and integration, ensuring that the system remains aligned with user needs and technical requirements (Schuh, 2004). Deployment of a pilot version (S3.2) in a controlled environment provides an opportunity to gather real-world feedback and identify any potential issues before full-scale implementation (Schuh, 2004). This pilot phase allows for the testing of not only the technical functionalities of the system but also its integration with existing workflows and information systems (Schuh, 2004).

For the information flow aspect, the focus remains on seamless integration and user empowerment. Integrating systems (I3.1) involves connecting the robot-based system with

existing information platforms used in the construction project, ensuring data compatibility and accessibility. Automating alerts (I3.2) ensure that critical information reaches the right people at the right time, facilitating timely responses and informed decision-making. Training users (I3.3) is essential to ensure that construction professionals can effectively utilize the system and interpret the data it provides. This involves providing clear instructions, hands-on training sessions, and ongoing support to empower users to leverage the system's full potential (Olfman and Bostrom, 1991).

The effectiveness of this phase should be evaluated through a combination of technical testing, user feedback, and performance monitoring to determine if the key decision question can be answered affirmatively (Nunamaker *et al*., 1990). Firstly, for the objective evaluation, performance testing evaluates the robot-based system's responsiveness, scalability, and stability under various load conditions, including load testing, stress testing, and endurance testing (Brogårdh, 2007). Then, for the subjective evaluation, User Acceptance Testing (UAT) involves end-users in validating that the system meets their needs and expectations in real-world scenarios, often through alpha and beta testing programs (Pandit and Tahiliani, 2015). Moreover, simulated environment testing creates a controlled setting that mimics real-world conditions to test the system's behavior before deployment (Žlajpah, 2008).

The key decision in this phase is: Is the system ready for wider deployment, and is the information flow secure and reliable? This decision, informed by the evaluation results, determines whether the development process can proceed to the final phase of monitoring and improvement.

4.4 Monitor and improve (S4.1 - S4.3, I4.1 - I4.3)
This phase embodies the concept of continuous improvement, a cornerstone of Toyota Production System, Lean Startup and Agile Development methodologies. It acknowledges that the journey of developing a robot-based system extends beyond initial deployment, encompassing ongoing refinement, adaptation, and optimization (Ávalos *et al*., 2019; Shore and Warden, 2021; Ohno, 2019). This perspective aligns seamlessly with the dynamic nature of the construction industry, where continuous improvement is essential for achieving long-term efficiency and effectiveness. By embedding this iterative mindset within the proposed framework, the robot-based system is aimed to remain relevant, valuable, and aligned with the ever-evolving needs of the construction industry, ultimately contributing to the realization of Lean Construction 4.0 principles.

Monitoring the system (S4.1) involves collecting data on its performance, usage patterns, and user feedback. This data provides valuable insights into how the system is being utilized, where it is excelling, and where there are opportunities for improvement (Piette *et al*., 2001). Refining the design (S4.2) based on this data ensures that the system remains aligned with user needs and preferences. This could involve adding new features, improving existing functionalities, or optimizing the user interface based on observed usage patterns and feedback (Drusinsky, 2011). Analyzing performance (S4.3) involves tracking key metrics to identify areas for optimization and efficiency gains. This could include metrics such as system uptime, data processing speed, user error rates, and information flow efficiency (Drusinsky, 2011). By identifying areas where the system can be improved, the development team can ensure that it continues to deliver maximum value to construction professionals.

For the information flow aspect, the focus remains on continuous optimization. Tracking metrics (I4.1) related to information flow, such as timeliness, accuracy, and accessibility, helps identify areas for improvement (Piette *et al*., 2001). Improving the flow (I4.2) could involve streamlining communication channels, automating information delivery, or providing users with more personalized information access (Madison, 2005). Evaluating the impact (I4.3) of the robot-based system and the optimized information flow on the overall construction process provides valuable insights into the system's effectiveness and its contribution to project goals (Madison, 2005).

The effectiveness of this phase is evaluated through ongoing monitoring, user feedback analysis, and impact assessment to determine if further optimization is needed. The subjective monitoring includes analyzing user feedback collected through periodic surveys, interviews, and feedback forms (Pandit and Tahiliani, 2015). In terms of objective monitoring, system usage data, such as user activity logs, feature usage frequency, and error reports, are analyzed to identify areas for improvement and potential new features (Madison, 2005). Multiple testing and evaluation methods can be employed for ongoing monitoring. Firstly, A/B testing can be applied to compare different design options and assess their impact on user satisfaction and system performance. Then, Key Performance Indicators (KPIs) related to system uptime, data processing speed, and information flow efficiency should be tracked to measure the system's effectiveness and identify areas for optimization (Madison, 2005; Parmenter, 2015). Additionally, the impact of the robot-based system and the optimized information flow on the overall process should be evaluated by measuring efficiency gains, cost savings, and improvements in decision-making (Madison, 2005).

The key decision in this phase is: Are there further opportunities to optimize the system and information flow? This decision, driven by the evaluation findings, guides the iterative nature of the proposed framework, ensuring that the robot-based system remains aligned with the evolving needs of the end-users.

5. Raising the hypothesis

Based on the proposed framework, this research aims to investigate the following null hypotheses to address the research questions:

H1. The application of the human-centered design framework for autonomous inspection robots is not able to lead to an improvement in system usability compared to existing inspection methods.

H2. The framework is not able to facilitate a more efficient information flow through a visualization approach, demonstrating the simplification of workflow and information flow processes.

H3. The use of autonomous inspection robots is not able to reduce human involvement in hazardous inspection tasks, leading to a reduction in waste and safety risks.

To ensure the validity of the hypothesis tests, several measures were implemented to create a controlled environment. For the usability evaluation (H1), the application of the human-centered design framework is the independent variable, and system usability is the dependent variable. System Usability Scale (SUS) questionnaires were administered under standardized conditions to all participant groups after each interaction with the robot-based system. This approach minimized variations in the testing environment, ensuring that differences in SUS scores could be attributed to the system itself. The case study tests this null hypothesis by comparing SUS scores of iterations of the robot-based system developed using the framework, with those of existing inspection methods. For the information flow efficiency evaluation (H2), the application of the framework is the independent variable, and the efficiency of information flow is the dependent variable. Here, value stream maps were constructed using consistent data collection methods and timeframes, which allowed for a direct comparison of the current and robot-based systems. The case study tests this null hypothesis by comparing value stream maps that visualize information flow with and without the framework's application. Finally, for the evaluation of human involvement in hazardous tasks (H3), the use of autonomous inspection robots is the independent variable, while human involvement in hazardous tasks, safety risks, and waste are the dependent variables. Data on task times were collected using a standardized protocol across iterations, ensuring that any observed changes reflected the impact of the robot-based system. The case study tests this null hypothesis by documenting and comparing the level of human involvement, safety risks, and waste before and after the implementation of the robot-based system.

6. Validating the hypothesis - case study

This case study demonstrates the application of the human-centered design framework for autonomous inspection robots in a real-world scenario. The project involved the inspection of a cell within a central infrastructure management facility in Alberta, Canada. This cell housed critical infrastructure components and the transfer of hazardous materials, including natural gas and wastewater, posing potential safety risks for human inspectors. Currently, this facility is scheduled for quarterly routine inspections with maintenance on request.

6.1 Project context and challenges

The central infrastructure management facility comprises a network of interconnected cells, each housing vital components for the operation of the facility. The selected cell for this case study has been posing significant challenges for manual inspection due to its confined spaces, complex layout, and the presence of potentially hazardous materials. Traditional inspection methods involve human inspectors entering the cell with specialized equipment, which pose safety risks and could disrupt operations. The project required a solution that could automate the inspection process, minimize human involvement in hazardous areas, and provide accurate and reliable data for informed decision-making.

6.2 Robot design and development

To address these challenges, a robotic system with a custom-built hexapod robot and a DJI Mini 4 Pro drone was designed and developed. The robot was equipped with LiDAR, RGB-D sensors, and a DHT22 sensor for collecting temperature and humidity data. The robot utilized frontier exploration for autonomous navigation (Yamauchi, 1997), and RTAB-MAP for Simultaneous Localization and Mapping (SLAM) (Labbé and Michaud, 2019). The SLAM map generated by the robot was then used for automatic path planning for the drone (Qin *et al.*, 2019), enabling it to conduct detailed inspections and capture high-resolution 4K images. These images were then processed using Bentley ContextCapture (also known as iTwin Capture Modeler) (Bentley, 2025) to reconstruct a 3D model of the cell, providing a comprehensive visualization of the inspected environment.

6.3 Framework application

The human-centered design framework was applied throughout the development and implementation of the robot-based inspection system. The case study involved 15 industry practitioners located in Alberta, Canada, with a minimum of eight years of experience in building management, infrastructure maintenance, facility management, or built environment inspections. The participants represented a diverse range of roles within the industry, including four current tradespersons working in maintenance, four foremen, three project managers, two department directors, and two regional portfolio managers. This study was approved by the University of Alberta Human Research Ethics Boards (Ethics ID Pro00147080).

6.3.1 Empathize and define. This phase aimed to thoroughly understand the needs and expectations of the end-users, ensuring that the proposed robotic inspection system aligned with the principles of Lean Construction 4.0. To achieve this, the participants were divided into two focus groups. The discussions within these focus groups were guided by a multi-faceted framework that incorporated the research objectives, the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh *et al.*, 2003), insights from 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). The UTAUT model, a widely recognized model for analyzing technology acceptance, served as a primary lens for shaping the discussion themes, focusing on performance expectancy, effort expectancy, social influence, and facilitating conditions to provide valuable insights regarding technology acceptance (Khechine *et al.*, 2016). This framework guided the exploration 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). Thematic analysis of the transcribed focus group data was facilitated by NVivo qualitative data analysis software and followed a structured, iterative coding process, involving open coding, axial coding, and selective coding, as shown in Figure 2. This rigorous analysis ensured that all relevant concepts and ideas expressed by the participants were captured, coded, and organized into a meaningful framework that accurately represented the data. The current workflow of inspection was evaluated by the end-users as 73.8. The findings from this stage are shown in Figure 3.

Based on the focus groups, the following requirements were summarized and approved by the end-users, as shown in Table 1. These requirements were ranked from the most important to the least, based on the contextual analysis.

To map out the information flow, a value stream map was created for the traditional inspection method. Value stream mapping is a lean tool that visually represents the flow of materials and information in a process, highlighting value-added and non-value-added activities (Rother and Shook, 2003). The value stream map for traditional inspections was drawn up based on the focus groups, along with the tasks and durations of all activities, as shown in Figure 4. Six participants from the central infrastructure management facility provided historical inspection records during the focus groups. These records included contracting documents, email communication logs, and inspection results for the selected cell.

A questionnaire that consists of SUS and level of human involvement was presented to the participants, at each time after the focus group. The usability of the robot-based inspection system was evaluated using SUS, which is a widely used questionnaire that measures the perceived usability of a system (Drew *et al.*, 2018). It consists of ten items, each with five response options ranging from "strongly disagree" to "strongly agree." The SUS scores range
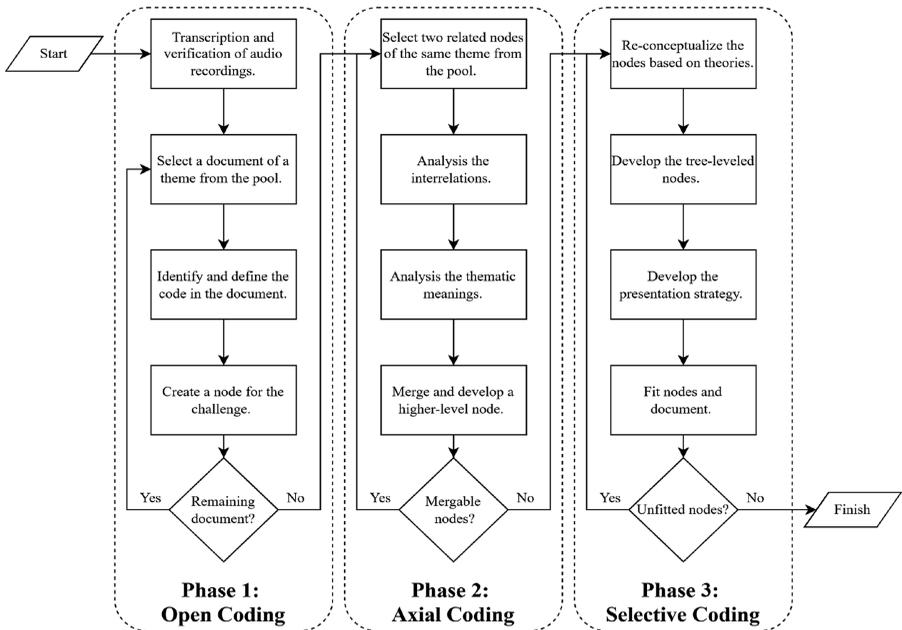

Figure 2. Inductive coding approach using NVivo, adapted from Bandara *et al.* (2015)

Workflow Tasks	Challenges	Expectations	Hesitations
Pre-Inspection			
Permit Acquisition	Equipment Availability	Automated Permit Processing	Initial Setup Cost
Safety Equipment Assembly	Contractor Qualification	Robotic Equipment Check	System Integration
Contractor Coordination	Safety Protocol Adherence	Remote Contractor Briefing	Training Requirements
Procedure Review	Rural Site Access	Virtual Site Preview	Regulatory Compliance
Execution			
Confined Space Entry	Limited Accessibility	Autonomous Navigation	Sensor Reliability
Visual Inspection	Hazardous Environments	Real-Time Data Feeds	Robot Durability
Sensor Monitoring	Visibility Constraints	Remote Operation	Signal Interference
Hazard Detection	Manual Data Recording	Multi-Sensor Integration	Navigation Errors
Documentation			
Observation Recording	Manual Data Transfer	Automated Data Logging	Data Security
Data Entry (FMS/CMMS)	Transcription Errors	Standardized Reporting	System Compatibility
Report Generation	Inconsistent Reporting	Cloud Data Storage	Data Management
Compliance Reporting	Data Accessibility	Data Visualization	Software Complexity
Follow-up			
Issue Assessment	Delayed Repairs	Predictive Maintenance	Cost of Predictive Analytics
Repair Scheduling	Coordination Difficulties	Automated Work Orders	Resistance to Change
Contractor Re-engagement	Budget Constraints	Data-Driven Insights	Data Interpretation
Verification Inspection	Lack of Data-Driven Insights	Streamlined Communication	System Integration

Figure 3. Summary of findings from the focus groups

Table 1. Summary of user requirements

Level 1	Level 2	Description
Access and mobility	Size and shape	Small, light, and compact to navigate tight spaces, narrow pathways, and obstacles
	Movement	Flexible and precise omnidirectional maneuvering
Sensing and perception	Scanning	Able to comprehensively map the area with automatic obstacle avoidance
	Robust sensors	Detect leaks or hazardous atmospheres
Data processing	Execution	Real-time navigation and object recognition
	Documentation	Automatic translation from raw data into the one usable for decision-making
User interface and control	Intuitive control	Easy-to-use interface
	Data visualization	Clear and concise display of sensor data
	Emergency rescue	Manual control or self-rescue procedures

from 0 to 100, with higher scores indicating better usability (Brooke, 1995). The level of human involvement in hazardous inspection tasks was assessed through a straightforward question which focused on the execution tasks of inspections. The questionnaire is shown in Table 2.
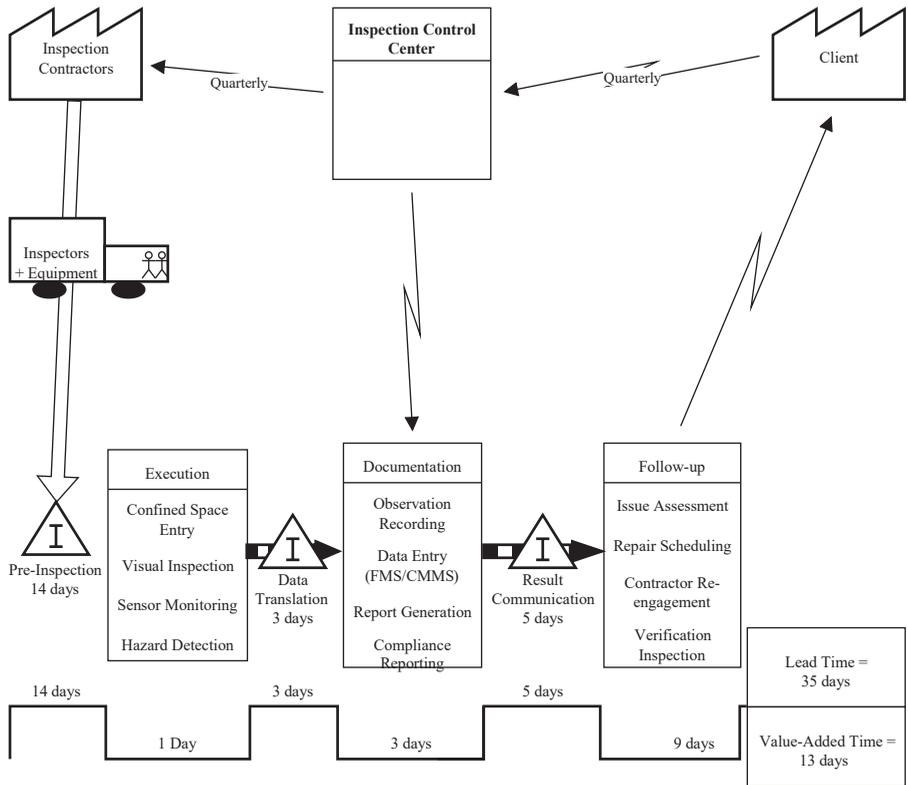
Figure 4. Value stream map for the current inspection workflow

Table 2. Questionnaire

Questions	Choices
A1. I think that I would like to use this system frequently	
A2. I found the system unnecessarily complex	
A3. I thought the system was easy to use	
A4. I think that I would need the support of a technical person to be able to use this system	
A5. I found the various functions in this system were well integrated	1–5
A6. I thought there was too much inconsistency in this system	
A7. I imagine that most people would learn to use this system very quickly	
A8. I found the system very cumbersome to use	
A9. I felt very confident using the system	
A10. I needed to learn a lot of things before I could get going with this system	
B1. Please estimate the percentage of time you would expect to spend on the execution tasks during the inspection	20%, 40%, 60%, 80%, 100%

6.3.2 Ideate and prototype. This phase was an iterative process of creative exploration, drawing inspiration from the Lean Startup methodology's "build-measure-learn" feedback loop (Avalos *et al.*, 2019). The goal was to rapidly generate and test a variety of design ideas,

gathering user feedback to guide the development of the robot-based inspection system (Ávalos *et al.*, 2019; Zorzetti *et al.*, 2022).

The process began with brainstorming sessions, where a multitude of concepts were sketched out, considering the robot's form, functions, and interactions, which are the core design aspects for robot system design. The team explored various interaction modalities, such as voice commands, touchscreens, and gesture recognition, to determine the most intuitive and user-friendly ways for construction professionals to interact with the robot. The focus was on understanding how the robot could best address the user requirements identified in the previous phase, such as accessing confined spaces, collecting data, and providing real-time feedback.

These brainstorming sessions led to the development of multiple low-fidelity prototypes in Nvidia Isaac Sim, a powerful platform for simulating robot behaviors in realistic environments (N. DEVELOPER, 2025). These prototypes allowed the team to visualize and test different design concepts, experimenting with various robot forms, sensor configurations, and interaction modalities. The prototypes were then presented to the end-users for evaluation through A/B testing and SUS questionnaires. This iterative feedback process allowed the team to identify the most promising design solutions and refine them based on user preferences and performance data.

Once a prototype achieved an average SUS score of 68, indicating acceptable usability as suggested by Bangor *et al.* (2009), the development process moved to the detailed designing stage. In this stage, the focus shifted to refining the design based on user feedback and technical considerations. The team carefully analyzed the human-robot interaction (HRI) design, focusing on communication modalities, control mechanisms, feedback mechanisms, and transparency of the robot's actions (Przemyslaw *et al.*, 2017). Safety considerations were also paramount, with thorough analysis of potential risks and the design of appropriate safeguards. Finally, the user-centered design was translated into detailed engineering specifications for the robot's hardware and software, ensuring that the final product would be both user-friendly and technically robust.

This stage involved three iterations, with SUS scores of 63.1, 72.4, and 75.2, respectively. By the end of this stage, the design of the robot-based inspection system had taken shape. A custom-built hexapod robot based on the Hiwonder Jethexa (Hiwonder, 2025) was chosen as the main platform for the system, and a DJI Mini 4 Pro drone (DJI, 2025) was selected for collecting information for detailed inspection as well as vertical inspection. The robot was equipped with LiDAR, RGB-D sensors, and a DHT22 sensor for collecting temperature and humidity data. Incorporating sensors with single sensing principles, such as temperature and humidity sensors, in this initial prototype was considered beneficial as it provided a foundational framework for integrating environmental data with SLAM, enabling the robot to assess basic environmental conditions and serving as a steppingstone towards more complex sensing capabilities for applications such as detecting thermal anomalies in industrial settings or identifying potential gas leaks.

The robot's ability to navigate autonomously was achieved through Frontier Exploration (Yamauchi, 1997). This is a method used in robotics for autonomous exploration, enabling the robot to make decisions about its next movement in an unknown environment. Frontier Exploration allows the robot to efficiently discover and map new areas by identifying the boundaries between known and unknown areas, referred to as "frontiers" (Yamauchi, 1997). By continuously seeking out and reaching these frontiers, the robot systematically expands its understanding of the environment (Yamauchi, 1997). This is crucial in complex inspection scenarios as it ensures the robot covers the entire inspection area effectively and methodically, without needing continuous human guidance, thus optimizing the inspection process and reducing the workload on human operators.

To simultaneously create a map of its environment and determine its own location within that map, the robot used RTAB-MAP (Labbé and Michaud, 2019). RTAB-MAP is a graph-based Simultaneous Localization and Mapping (SLAM) solution designed for large-scale and

long-term online operation (Labbé and Michaud, 2019). It utilizes both lidar and visual data, and potentially other sensor inputs, to achieve robust and accurate mapping and localization (Labbé and Michaud, 2019). This is achieved by creating a graph representation of the environment, where nodes represent locations and edges represent relationships between these locations. Loop closure detection, a key feature of graph-based SLAM, allows the robot to recognize previously visited locations, correcting accumulated errors and improving map accuracy (Labbé and Michaud, 2013). This process is crucial for the robot to maintain awareness of its position within the inspection environment, avoid obstacles, and effectively plan its navigation path, especially in dynamic or unstructured settings.

The SLAM map generated by the robot played a crucial role in enabling the drone to conduct detailed inspections. This map provided a spatial understanding of the environment, which was used for automatic path planning for the drone (Qin *et al.*, 2019). This allowed the drone to navigate the environment efficiently and systematically, ensuring comprehensive coverage while capturing high-resolution 4K images. These images were then processed using Bentley ContextCapture (Bentley, 2025). Bentley ContextCapture, also known as iTwin Capture Modeler, is a software solution that employs photogrammetry techniques to reconstruct detailed 3D models from images. By analyzing the relationships between overlapping images captured by the drone from various viewpoints, the software can accurately generate a textured 3D model of the cell (Bentley, 2025). This process results in a comprehensive and visually rich representation of the inspected environment, enabling detailed analysis, measurement, and visualization of the inspected space, which is essential for effective infrastructure management and decision-making (Khan and Khan, 2011; Chen *et al.*, 2008).

6.3.3 Develop and deploy (S3.1 - S3.3, I3.1 - I3.3). After passing the Ideate and Prototype stage, the team moved to the Develop and Deploy stage, where the focus shifted from simulated environments to real-world implementation. A cell within a central infrastructure management facility was chosen as the testbed for this stage. The selected cell posed significant challenges for manual inspection due to its confined spaces, complex layout, and the presence of potentially hazardous materials. Traditional inspection methods, involving human inspectors entering the cell with specialized equipment, posed safety risks and potential operation disruptions. The project required a solution that could automate the inspection process, minimize human involvement in hazardous areas, and provide accurate and reliable data for informed decision-making.

The experiment involved not only the cell itself but also a tunnel that provided access to the cell. This allowed for a comprehensive evaluation of the robot's capabilities in navigating and collecting data in various environments. The team tested both autonomous and manual data collection methods, resulting in a multi-layer model that consisted of a 3D model, a SLAM layer, and a sensor layer, as shown in Figure 5. This multi-layer model provided a rich and comprehensive representation of the inspected environment, capturing not only the visual details but also the robot's trajectory and sensor readings.

After refining the system based on initial testing and feedback, the robot-based system achieved a SUS score of 82.9 in this stage, surpassing the score of 73.8 for the current inspection workflow. This indicates a significant improvement in usability, achieving an "Excellent" rating in the adjective ratings and "Acceptable" in the acceptability range Bangor *et al.* (2009).

6.3.4 Monitor and improve (S4.1 - S4.3, I4.1 - I4.3). The Monitor and Improve phase is an ongoing process that emphasizes the continuous improvement of the robot-based inspection system and the information flow process. While this phase is planned for the future and is yet to be documented, the following measures are currently planned to guide the monitoring and improvement efforts:

Gathering Feedback (S4.1): To gather comprehensive feedback on the system's performance and user experience, several measures will be employed. Participants are encouraged and invited to make appointments to use the robot-based system on a regular basis. User surveys and
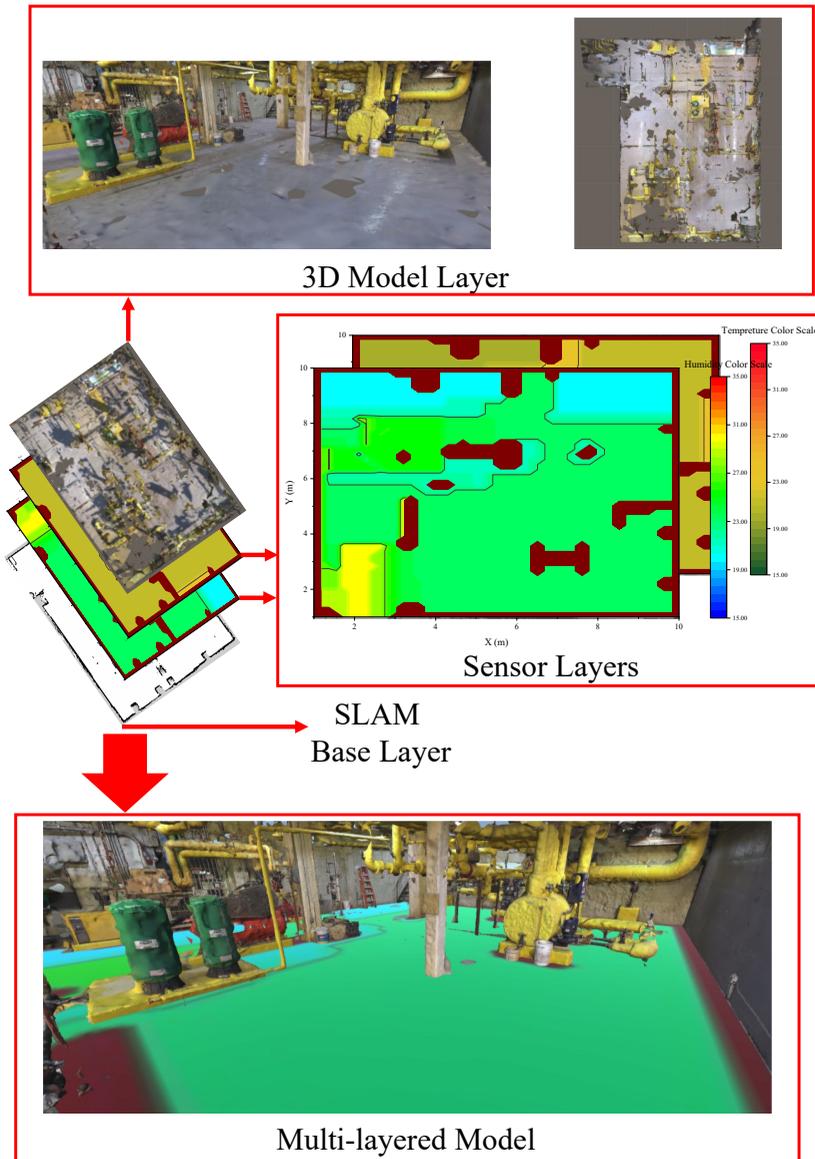
Figure 5. Multi-layer model

interviews will be conducted to gather qualitative data on usability, efficiency, and effectiveness (Drusinsky, 2011). System logs and performance data will be analyzed to identify areas for improvement and potential issues. User interactions with the system will be monitored to understand usage patterns and identify areas of confusion or difficulty.

Refining Design (S4.2): Based on the gathered feedback, the design of the robot, its sensors, and its user interface will be refined to improve usability and address any identified issues. The robot's navigation and data collection algorithms will be optimized to enhance

efficiency and accuracy. New features and functionalities will be developed based on user feedback and emerging needs.

Analyzing Performance (S4.3): KPIs such as inspection time, data accuracy, and robot uptime will be tracked to assess the system's effectiveness (Madison, 2005; Parmenter, 2015). Comparative analysis with traditional inspection methods as well as previous generations of robot-based systems will be conducted to quantify the benefits of updating (Madison, 2005). The long-term performance of the system will be monitored to identify trends and potential areas for improvement (Madison, 2005).

Tracking Metrics (I4.1): The timeliness of information delivery will be tracked to ensure that stakeholders receive critical information promptly. The accuracy and completeness of the information provided by the robot-based system will be monitored and evaluated. The accessibility of information to different stakeholders will be assessed, ensuring that information is readily available to those who need it.

Improving Flow (I4.2): Bottlenecks in the information flow process will be identified and addressed, streamlining communication channels and optimizing data transfer (Madison, 2005). Automated reporting and data visualization tools will be implemented to enhance the clarity and accessibility of information, referring to the work conducted by Piette et al. (2001). Collaboration and communication among stakeholders will be fostered to ensure that information is shared effectively and used to inform decision-making.

Evaluating Impact (I4.3): The impact of the improved information flow on the overall project performance, including efficiency gains, cost savings, and improved decision-making, will be assessed. User satisfaction with the information flow process will be evaluated, gathering feedback on clarity, timeliness, and relevance (Pandit and Tahiliani, 2015; Madison, 2005). The long-term impact of the improved information flow on project outcomes and stakeholder satisfaction will be monitored.

6.4 Hypothesis testing
This section presents the analysis of the data collected during the case study to validate the hypotheses proposed in Section 4.

6.4.1 Usability evaluation. The SUS questionnaire was administered to the participants of the focus groups each time after they had interacted with the robot-based system. The results showed that the system achieved a SUS score of 82.9, surpassing the score of 73.8 for the current inspection workflow, as shown in Figure 6. This indicates a significant improvement in usability, achieving an "Excellent" rating in the adjective ratings and "Acceptable" in the acceptability range Bangor et al. (2009). This finding rejects null hypothesis H1, showing that the application of the human-centered design framework would lead to a significant improvement in system usability.

6.4.2 Information flow efficiency and value generation evaluation. To evaluate the efficiency of information flow, a value stream map was created for the robot-based system, based on the documentation from the trail deployment as discussed in Section 5.3.3. In this value steam map, as shown in Figure 7, the pre-inspection activities included setting up the robot system, deploying the hexapod robot as well as the drone, and the maintenance.

This value stream map for the robot-based system was compared to the one for current inspection workflow, as shown in Figure 4, to identify differences in lead time and value-added time. Lead time is the total time it takes for a process to complete, from start to finish (Rother and Shook, 2003). Value-added time is the amount of time spent on activities that directly contribute to the value of the inspection service (Rother and Shook, 2003). The comparison of the value stream maps showed that the robot-based system significantly reduced the lead time for inspections from 35 days to 13.125 days, indicating an improvement of 62.5%. Consequently, the flow-time efficiency increased from 40% in the current inspection workflow, to 76.2% by using the robot-based system. Moreover, the inspection control center can directly monitor and control the execution of inspections in the robot-based system, which
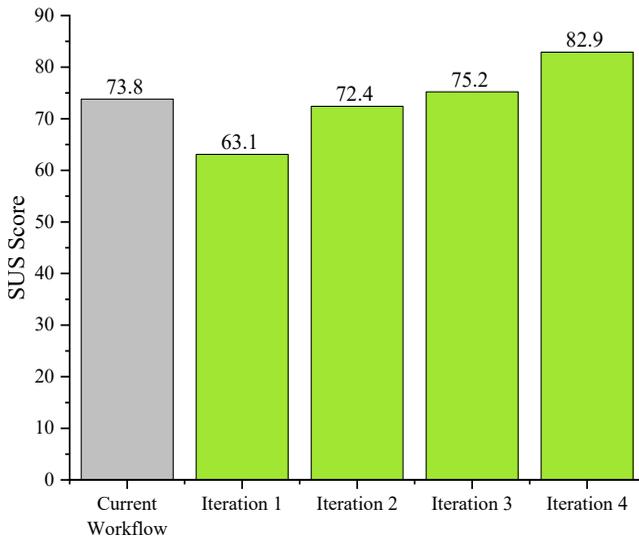
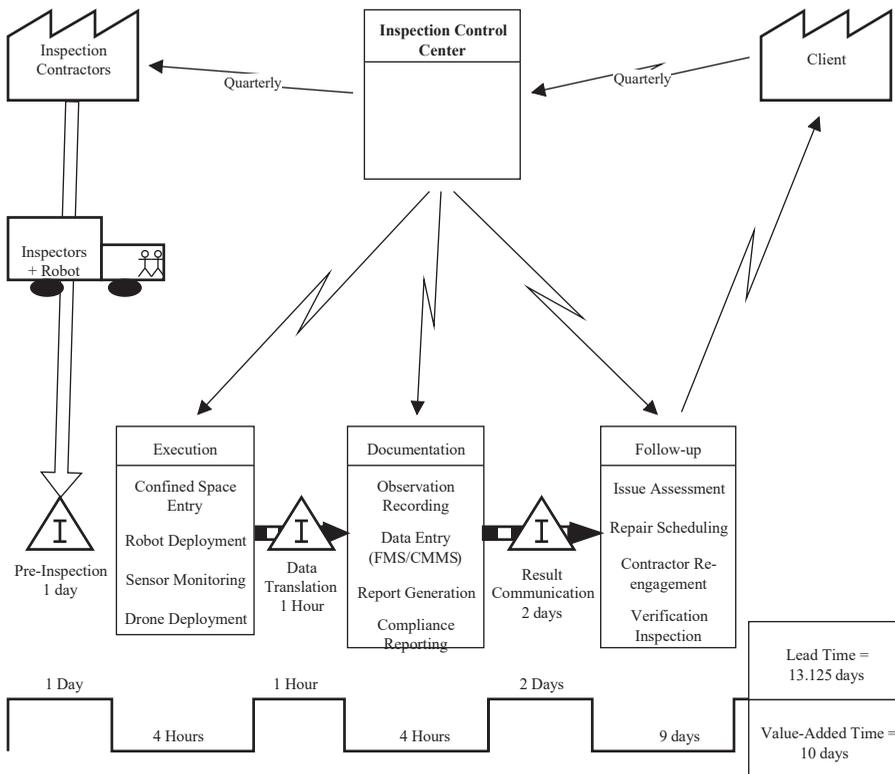**Figure 6.** SUS scores of the current workflow and iterations

Figure 7. Value stream map for the robot-based system

increases the transparency of these activities. The improvements in flow-time efficiency as well as the inspection transparency indicated a substantial enhancement in information flow efficiency, rejecting null hypothesis H2, which stated that the framework would facilitate a more efficient information flow.

6.4.3 Minimization of human involvement in hazardous inspection tasks and safety improvement evaluation. To assess the impact of the robot-based system on minimization of human involvement in hazardous inspection tasks and safety improvement, data on the time required for manual inspections was collected from the focus groups and compared to the iterative data from the robot-based inspections. Figure 8 illustrates the impact of autonomous inspection robots on reducing human involvement in hazardous inspection tasks. The data is derived from focus groups by using the questionnaire in Table 2, which provides a baseline for manual inspection times, and iterative data collected during the implementation of the robot-based system. By comparing these data sets, the figure visually demonstrates a significant decrease in human involvement in hazardous tasks as the robot system is refined through iterations. In essence, Figure 8 highlights the safety improvements achieved by deploying autonomous robots for inspections. The figure uses a comparative approach, contrasting traditional manual inspection methods with the evolving implementation of robot-based inspections. This comparison underscores the robot-based system's effectiveness in minimizing risks to human workers by automating hazardous tasks. After four iterations, the robot-based system reduced the level of human involvement in hazardous inspection tasks from 94.67% to 38.67, indicating an improvement of 59.16%. This rejects null hypothesis H3, showing that the robot-based system developed in accordance with the proposed framework is able to reduce human involvement in hazardous inspection tasks.

7. Discussion

The findings of this study provide compelling evidence for the effectiveness of the human-centered design framework for autonomous inspection robots in advancing the goals of Lean Construction 4.0. By integrating theoretical principles of Lean Construction 4.0 into a cohesive framework that addresses the multifaceted nature of robot-based system development, specifically in terms of human-centricity, data-driven decision-making, and
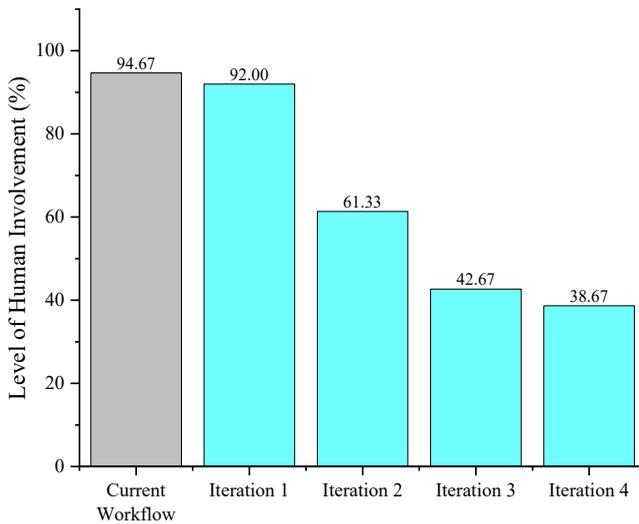

Figure 8. Level of human involvement in hazardous inspection tasks of the current workflow and iterations

continuous improvement, the framework offers a holistic approach to developing and implementing robot-based systems that are not only technically usable but also user-centered, adaptable, and value-driven. Grounded by the principles of TFV (Koskela *et al*., 2007), Human-Centered Design with design thinking (Cooley, 2000; Brown, 2008), Lean Startup (Ávalos *et al*., 2019), and Agile Development methodologies (Zorzetti *et al*., 2022; Al-Saqqa *et al*., 2020), the proposed framework demonstrates its ability to effectively integrate human-centered design, value-driven development, adaptability, and information flow management in the development of robot-based systems.

The case study demonstrated that the application of the framework resulted in a robot-based inspection system that significantly improved usability, enhanced information flow efficiency, reduced human involvement in hazardous inspection tasks and safety risks, and ultimately increased value generation. These findings underscore the potential of robot-based systems to transform construction processes, particularly those that are essential but may not directly contribute to the final built product, such as inspections. By automating these tasks, robot-based systems can free up human workers to focus on more complex and creative tasks, ultimately leading to a more efficient, sustainable, and human-centered construction industry.

Moreover, the findings highlight the importance of human-centered design in the development of robot-based systems. By actively involving end-users in the design process and prioritizing their needs and preferences, the framework ensures that technology serves to enhance human capabilities rather than replace them. This approach fosters a collaborative environment where technology and humans work together to achieve common goals, paving the way for a more harmonious and productive future for the construction industry.

To maximize the impact of the proposed human-centered design framework, construction practitioners and technology developers should prioritize early and continuous stakeholder engagement to ensure alignment with user needs and project goals. Establishing cross-disciplinary teams, including construction professionals, roboticists, and human factors experts, can enhance the framework's adaptability to diverse construction scenarios. Additionally, organizations should invest in training programs to build workforce competency in interacting with autonomous inspection robots, addressing hesitations identified in the focus groups. To further refine the framework, pilot implementations should be conducted across varied construction environments, such as urban high-rise projects or remote infrastructure sites, to validate its scalability and generalizability. Finally, integrating emerging technologies like AI-driven analytics and multi-sensor fusion, as suggested for future research, should be pursued incrementally to balance innovation with practical deployment constraints.

The implications of this research extend beyond the specific context of the case study. The framework presented in this paper provides a valuable tool for construction practitioners and technology developers seeking to integrate robotics into their workflows. By adopting a human-centered and iterative approach, they can ensure that robot-based systems are developed and implemented in a way that maximizes their benefits while minimizing potential risks and disruptions.

8. Conclusion

This research presented a human-centered design and development framework for autonomous inspection robots in Lean Construction 4.0. The framework provides a structured and iterative approach for developing and implementing robot-based systems that are human-centered, value-driven, adaptable, and information-driven. The case study demonstrated the effectiveness of the framework in achieving significant improvements in usability, information flow efficiency, waste reduction, safety, and value generation. The findings support the hypotheses that the framework can successfully guide the development and implementation of robot-based systems that contribute to the realization of Lean Construction 4.0 goals.

This research contributes to the growing body of knowledge in Lean Construction 4.0, demonstrating the potential of advanced technologies to support lean principles and enhance construction processes. By integrating human factors, information flow management, and value generation into the design and implementation of robot-based systems, this framework provides a practical roadmap for achieving the goals of Lean Construction 4.0 and creating a more sustainable and human-centered construction industry.

Despite the contributions, this research has certain limitations. The case study focused on a specific construction scenario, and the findings may not be generalizable to all types of projects. The sample size for the focus groups and system evaluation was limited, which may affect the statistical significance of the results. Additionally, the research primarily focused on the development and deployment of the robot-based system, with the Monitor and Improve phase planned for future work.

Future research should focus on expanding the case study to different construction scenarios and conducting larger-scale evaluations with more diverse participant groups. The effectiveness in decision-making aid for the robot-based system developed in this paper should be thoroughly assessed. The Monitor and Improve phase should be implemented and documented, and the long-term impact of the framework on project outcomes and stakeholder satisfaction should be assessed. Additionally, future research could explore the integration of more advanced technologies, such as artificial intelligence, multi-sensor fusion, and swam of robots, into the framework to further enhance the capabilities of robot-based systems in construction.

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