

Implementation of a Robotic System for Overhead Drilling Operations: A Case Study of the Jaibot in the UAE

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Abstract

Robots have typically improved workers' health and safety and increased productivity and quality in manufacturing. Current advances in robotic and computer technology, combined with BIM, have led to new applications in construction. However, there is no general framework to guide the implementation of robots under current construction working schemes. Many questions and challenges need to be answered and overcome before robots can be economically and safely introduced to construction sites. Some questions include: 1) How does it affect the planning and workflow of related activities? 2) What are the implications regarding health & safety, and quality? 3) What is the best way to assess the viability of introducing robots onsite? 4) What are the organizational implications of using such systems? Still, there is plenty of work to do when considering common project management elements when using robots. To assist with that, this paper presents a case study in which we gathered real-world data on the overhead drilling work of an on-site semi-autonomous robot. In addition to the traditional analyses for changes in workflow, productivity, health & safety, and quality, as well as the implications to the schedule and cost of the tasks carried on by the robotic system, this study proposes a project management framework to help contractors better prepare for the introduction of robotic systems into their projects when similar scenarios arise. In addition, this study gives an insight into human-robot interaction experiences in real construction projects.

Keywords –

Project Management Framework; Productivity; Semi-autonomous Drilling Operations; Construction Robots

1 Introduction

The use of robots in the construction industry has been considered for quite some time to handle inefficiencies and low productivity. Technology advancement in construction is changing how a project is carried out, as a considerable amount of on-site work can be conducted automatically. However, many factors limit the wide adoption of robotics in the construction industry, such as incompatibility of technologies, the fragmented nature of the construction, and high initial capital investment [1]. In addition, due to the multidisciplinary and complex nature of construction projects, robotic systems and automation technology are often not general [2], there are no consistent methods to sufficiently analyze the feasibility and efficiency of the robotic system to be used [3]. In previous research, the emphasis on implementing construction robotics has been mostly on identifying technological issues and challenges [4]. The interaction between robotic systems with management and human factors may raise new interest in future research. In the meantime, to support the project and business decision on robotic adoption, a generalized framework for robotic-oriented management is also needed.

This research uses a case study related to the engineering, planning, and production data of a concrete drilling robot in a real project to help the industry figure out a solution and a framework to review and advance the usage of robots in a systematic manner. The research methodology used is summarized in Fig. 1. In general, it consists of a literature review and a single case study from which qualitative and quantitative data were collected and analyzed. Qualitative includes basic project information, the usage of the robotic system, the planning and organizational procedures, and the stakeholders' opinions from interviews. Quantitative data came from the robot's task reports, which detailed information such as time in operation and the number of holes drilled.

Based on previous literature, a comprehensive

feasibility analysis was carried out to assess the drilling robot in the case study. We involved a feasibility analysis procedure in helping decision-makers evaluate and decide the implementation of the new robotic system. This study investigates the impacts of utilizing robots based on the conventional performance criteria such as productivity, health & safety, and accuracy. Then we identified challenges that limited the adoption and proposed solutions to overcome the challenges. Based on these procedures, we proposed a systematic framework for robotic-oriented management to optimize the outcome of the robotic construction.

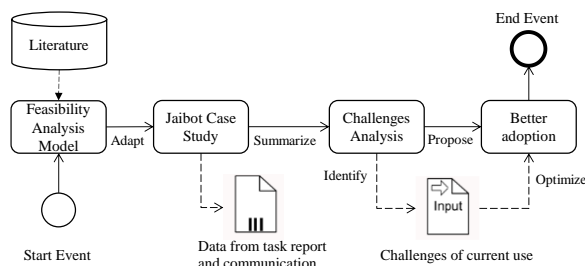


Fig. 1 General structure of the research methodology used in this study.

2 Feasibility analysis model

With the introduction of new technologies, it is critical to analyze the potential and actual impact of that technology (e.g., the deployment of robots in construction sites). In this work, we present a feasibility analysis model for the general adoption of construction robotics. The feasibility analysis model sets up a modeling procedure to evaluate the feasibility of developing robotics and justifying their implementation for certain construction operations [5]. The feasibility analysis model consists of three key elements: project description, performance criteria analysis, and human factors analysis, as shown in Fig. 2.

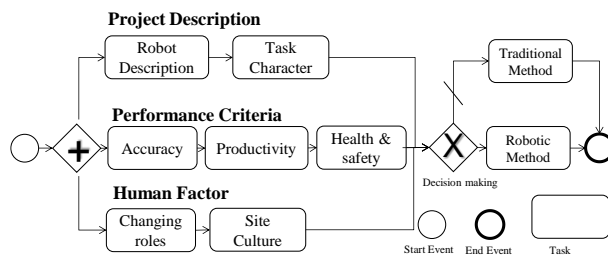


Fig. 2 Feasibility analysis model

2.1 Project Description

The adoption of construction robots is project-oriented [6]. In the project description stage, a comprehensive analysis should be made to identify the

construction automation levels of robotics [2]. A robotic system generally comprises many modules working together to perform a task. The description of the robotic system should list the basic structures as well as functionalities and capacity of the robot to show potential usage in specific tasks. Principles of the tasks and influences from the environment will highly influence the robot's performance [7]. Task characteristics should be defined for coordination with the robots.

2.2 Performance Criteria

2.2.1 Accuracy

Using robots in construction sites can minimize mistakes caused by human errors and help improve accuracy [8]. Still, with advanced technology, robots can fulfill repetitive work with high speed and accuracy; fewer mistakes will result in fewer delays and repair/rework activities [9], also will lead to more enduring construction structures [10].

2.2.2 Productivity

Previous research has utilized productivity as an important metric to analyze the adoption of construction robots. For example, García de Soto et al. [11] presented a productivity analysis based on the robotized construction of a reinforced concrete wall. Usmanov [12] studied the productivity impacts of an automated bricklaying robot versus the traditional construction method. Previous research has shown that higher-level automation allows construction managers (CMs) to plan their projects more effectively, provide an easier way to meet deadlines, and save time and financial resources. However, a construction project is unique. The uncertainty caused by design changes, dynamic environment, and human activities will greatly influence the outcome.

2.2.3 Health & Safety

Robotic systems can reduce injuries and free workers from conducting dangerous tasks [13]. Moreover, workplace safety will be improved by replacing workers with robots in tasks that involve difficult physical work or exposure to unhealthy environments. Although so many benefits, robots work simultaneously with humans when we implement robots on the construction site. This will cause management issues and safety concerns when humans and robots interact in the same environment [14].

2.3 Human factors

2.3.1 Changing roles

The advent of robots within different construction processes will offer opportunities to people who have a strong interest in new technologies, but at the same time,

it will cut a considerable number of on-site jobs. Robotic machinery cannot fully replace human presence, but it can reduce it significantly [1]. Also, it is expected that current construction roles will evolve, and new roles will be created [16]. New roles such as digital model designer and robotic expertise will take more responsibilities during the construction process.

2.3.2 Worker's attitude towards change

Performing human-robotic collaborative tasks require workers to have the ability to understand how to achieve team coordination and communication with the robotic system, effectively monitor the construction process by recognizing problems, and intervene during certain circumstances. Thus, the construction labor markets will turn to specialists and qualified employees, and job security issues could result in workers' aversion to change in the construction culture [1].

3 Case Study: Jaibot for overhead drilling operations

To assess the real-world implementation of on-site construction robots, we conducted a case study in collaboration with ALEC Engineering & Contracting (ALEC), a construction company in the United Arab Emirates, and Hilti, a company that develops and manufactures products for the construction industry.

3.1 Project description

The project used for this study is the One Za'abeel in Dubai, consisting of 2 skyscrapers, Tower A and Tower B. To promote innovation and digital transformation in the construction industry, ALEC, the main contractor of the project, attempted to adopt a semi-automated robotic system, the Jaibot by Hilti, to complete overhead drilling operations for the subsequent installation of MEP systems. The real-site robotic execution on Tower A took place in September 2020.

3.1.1 Robotic description

Table 1 summarizes the key information about the Jaibot with the basic functions and capabilities.

Table 1 Summary of Jaibot features

Component	Function	Capacity
Drill	Drilling	Holes (6 – 16 mm).
Total station	Position	Locate drill bit within an accuracy of ± 5 mm.
Robotic Arm	Stretch	2.65 – 5.0 m above.
Jobsite tablet	Control	Move the robot
Hilti's cloud service	Instruct the robot	Locate drill position; Progress updating

The Jaibot is a semi-automated construction robot designed for mechanical, electrical, plumbing, and interior finishing installation work. Based on the information provided by ALEC, the robot starts with coordinating the tasks, including collecting design information from BIM models and setting reference points. When it comes to the real site execution, design files are loaded wirelessly via Hilti's control panel and downloaded from Hilti's cloud service. After arriving at each workstation controlled by the operator, the robot will reach and drill all the identified holes automatically based on the specifications.

3.1.2 Task characteristic

The work was taking place on an ongoing construction site with multiple operations underway and multiple subcontractors. As a result, some obstructions prevented the completion of the full levels at one time. ALEC defined four levels of Tower A in which overhead holes with different diameters (12mm and 15mm) were drilled for subsequent installation of MEP elements. There were 3,488 holes planned. The size of the holes was designed to standardize the drill diameters and control the quality. The allocation of each hole type and their number per level are summarized in Table 2. By the time of this research, the total number of holes drilled in this project was 3,058. For this study, we only considered the holes drilled between levels 34-37 (1,537 holes).

Table 2 Size and numbers of holes to be drilled.

Hole size	Level			
	L34	L35	L36	L37
12 mm \varnothing	628	638	638	646
15 mm \varnothing	236	234	234	234

3.2 Performance criteria

3.2.1 Accuracy

The system recorded details of each hole drilled. This includes location (x, y), depth (z), and diameter. All this information could be observed in real-time on the dashboard provided by Hilti.

The drill diameter or depth did not cause any deviations in the current practice, as the diameter was based upon the drill bit. Holes remained the same size until the drill bit was changed. When applicable, the drill bit was replaced by the operator. The depth was preprogrammed, and the robot automatically notified the operator if the depth could not be achieved.

Factors that influence the robotic drilling include calibration errors in the total station, errors from the ceiling plane sensor, accuracy in planning (BIM), and human errors on robot control. For instance, planning and communication errors led to deviations between as-

planned BIM coordinates and as-built coordinates, which impacted the robot accuracy because the robot could not tell whether the site conditions differed from the BIM model; it would continue to drill according to plan without notifying the variance.

3.2.2 Productivity

3.2.2.1 Basement test

In the early stages of evaluating the capabilities of the Jaibot, a demonstration was done in the basement to compare traditional and robotic drilling methods for productivity analysis. The list of tasks and workflow for drilling operations using manual or traditional techniques are summarized in Fig. 3.

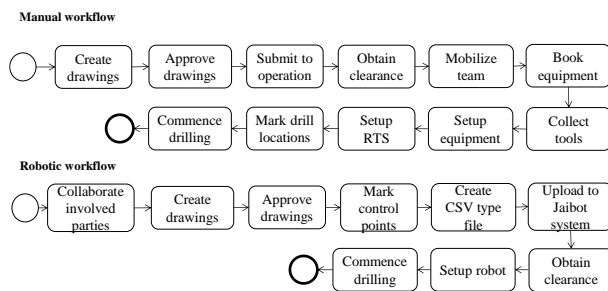


Fig. 3 Workflow of manual and robotic drilling operations

Based on the task report from ALEC, the manual drilling process took about 270 seconds, with a cost of 5.85 AED per hole. Robotic productivity was measured using the same parameters as human workers. For an 8-hour working day, at least 400 holes were drilled, which shows the productivity of the robot is at most 72 seconds per hole. The cost for renting the robotic system is 2,500 AED/day. This information is summarized in Table 3.

Table 3 Comparison between Jaibot and traditional method during the test at the basement

Method	Productivity	
	Cost (AED/hole)	Duration (sec/hole)
Traditional	5.85	270
Robotic	6.25	72

From the production data in Table 3, the Jaibot reduces the duration of the drilling process from 270 secs/hole to 48 secs/hole, which shortens the on-site drilling process. This can also be explained by comparing the workflow of two procedures (Fig. 3). The big differences between the two methods rely on the process of marking the drilling positions instead of manual marking based on the drawings; the robot could easily find references from pre-defined control points. That is less time-consuming and more reliable (i.e., reducing

human errors). However, the cost and duration for the preparing stage, such as collaborating with all parties, initializing the BIM models (insert drill depth in terms of the requirements of the robot), setting up cloud service and equipment, are not yet considered in this test. Further analysis needs to be conducted when robots come into the real site.

3.2.2.2 On-site execution

After accessing the Jaibot data with the real construction process, the productivity was not as great as expected. Although detailed information on the preparing stage was not available, some of the reasons include the time used for transporting the robot or cleaning the job site. In the task report, only the effective construction duration with successful holes drilled was considered to calculate the productivity.

One thousand five hundred thirty-seven holes were completed with the Jaibot in 9 days. The task report indicated that the average daily hours operated by the robot (e.g., in Fig 4) were about 3.86 [hours per day].

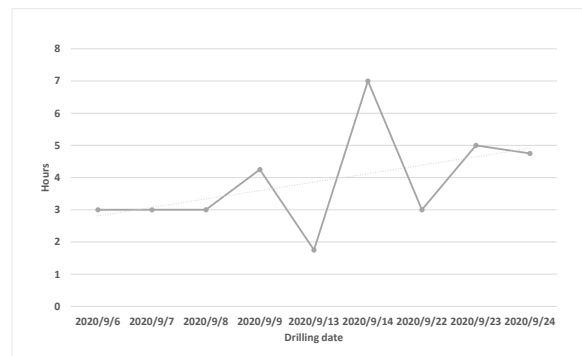


Fig. 4 Working hours of Jaibot during the testing period

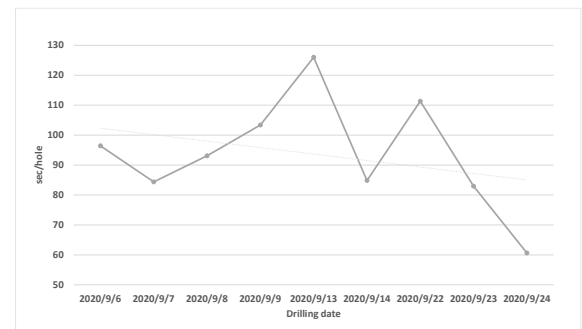


Fig. 5 Production rate of Jaibot during the testing period

With the number of holes drilled each day stated in the task report, we can calculate the production rate and compare it with the experimental ones. From Fig 5, we

have an average productivity of 86.5 secs/hole, which is not as good as the 48 secs/hole base experiment.

The deviation comes from multiple aspects. For example, the current workflow is not as smooth as the planned ones. The design and operations teams must be aligned with all schedules (civil works, subcontractor packages, design packages, client signoff, etc.) to ensure the work area is ready; however, design changes usually occur while the project is underway, which can cause a major delay.

Besides, holes could fall out of accuracy requirements due to errors in sensing or differences from the original design. In addition, site managers might decide to skip the holes due to awkward positions (for example, if a drill operation hit rebar and did not penetrate fully). Among the 1,537 holes drilled, 96 holes failed for certain reasons. On average, the failure rate was 6.71% for the 9 days. Failed holes and skipped ones could result in a great amount of time to be remeasured and reevaluated. These failures will greatly influence productivity.

3.2.2.3 Longer operation better productivity

To find a general reason why the productivity varies in these 9 days, we conducted the further analysis. From Fig. 4 and Fig. 5, we can see that, on 09/13/2020 and 09/22/2020, the working hours are the least among the 9 days, with 1.75 and 3 hours, respectively. On those days, the production rate is the lowest (126 secs/hole and 103 secs/hole), which indicates the drilling process takes longer in these two days. In contrast, on 09/14/2020, there was a significant increase in the working hours to 7 hours and a significant increase in the production rate to 84.84 secs/hole. Therefore, it could be stated that with more time the robot drilled, the required duration for drilling one hole would be less. To verify that conjecture, we calculated the Pearson's Correlation Coefficient (r) to identify any linear correlation between these two sets of data. The result shows that Pearson's Correlation equals -0.608. A strong negative relationship between these two parameters indicates that longer operation will have a greater probability of better productivity for robotic drilling. Many reasons could cause the longer manipulation of the robot, for example, open area that is easy for the robot to transform; skilled operator on duty that facilitates the process; smoother schedule with less intervention of surroundings; or the drilling position is easy to access with less failure or skip. With limited information right now, we could not find the exact reasons; also, the sample size is rather small, which does not allow for a generalization of the results obtained.

3.2.3 Health and Safety

Robotic drilling improved the task ergonomics, reducing the muscle strain work hours (measuring and drilling overhead). It can reduce the Work-Related Musculoskeletal Disorder conditions and vibrations.

Based on Hilti's feedback, the Jaibot could also reduce noise levels from the drill bits and distanced the workers from the source of drilling noise. Besides, the robot's modular integrated vacuum could reduce workers' exposure to respirable crystalline silica and dust, providing a better working environment for on-site construction.

Based on an interview with ALEC's site team, they gave an overall high evaluation of the health and safety performance of the Jaibot. 90% of the interviewees strongly agree that the Jaibot is reliable on safety performance. However, in another set of questions regarding the adoption of construction robots for applications of all kinds, some interviewees were concerned about safety when working with construction robots. One of the reasons for that could be that there is not much experience with real-world robotic applications in construction projects. Thus, when operating in the same environment as robots, workers might feel uncertain or insecure in such environments. Besides, construction sites are dynamic and hard to control environments; unexpected health and safety issues could come out because of human errors or omissions when dealing with onsite robotic systems or vice versa.

3.3 Human factors

3.3.1 Changing Roles

As part of its role as the main building contractor, ALEC facilitated coordination and communication among the different project participants. In addition to conventional tasks, such as defining a site management strategy or the work scope, ALEC had to put extra effort into communicating work packages with different parties, setting up communication among subcontractors and Hilti to ensure proper integration of the Jaibot. Subcontractors also had to adjust their workflows to incorporate the requirements from the robotic system.

For example, ALEMCO was the subcontractor responsible for installing the MEP package on Tower A. The Jaibot team operated as an additional subcontractor, collaborating with other trades on site. ALEMCO used the IFC files from the base design supplied by the client and developed a BIM model for coordination and building procedures, also used for the robotic tasks. ALEMCO was responsible to define a reference system in the form of a building axis for the robot to use. They also created a CSV-type file to be used by the Jaibot. Hilti's Jaibot team also had several roles during this process. They provided skillful operators for on-site support for the robotic system and gave valuable feedback on monitoring and control processes during the robotic adoption. For instance, the site team of Hilti coordinated with the site surveyor to define the measuring process. Meantime, the team should have the

list of prerequisites delivered to the main contractor to get the necessary support on the job site.

3.3.2 Worker's attitude towards change

To better understand the workers' attitudes towards changes due to the use of the Jaibot, we conducted a questionnaire to gather extra information. A copy of the questionnaire can be found in [15]. The questionnaire consisted of 40 questions broken down into eight parts, namely (1) Performance; (2) Compatibility; (3) Challenges; (4) Organizational support; (5) Technical Support; (6) Regulatory & public support; (7) Attitudes towards adoption; and (8) Industry atmosphere.

The questionnaire was distributed to the site team of ALEC and Hilti. Eight responses were provided during the time we worked on the research. Hilti representatives operated the Jaibot. This could be a problem that limited future adoption; drilling workers might not be compatible with new roles to operate the robot. New organization support needs to be established to raise more interest in robotic learning and practice. Attitude mostly comes from operators, modelers, and managers, which shows that robotic adoption will not greatly influence their job opportunities; however, the manual drilling workers' job opportunity is lost. Thus, the management framework needs to acknowledge these changing roles.

4 Jaibot adoption optimization

To solve the problems mentioned in the previous section. Based on the literature review, we summarize the current challenges of Jaibot adoption and put forward strategies to overcome such problems.

4.1 Performance criteria

4.1.1 Accuracy

As previously defined, errors were coming from sensing strategy in state estimation for robotics. To increase accuracy and robustness, a growing number of applications have started to rely on data from multiple complementary sensors. For example, Furgale and Siegwart [17] proposed a unified method of determining fixed time offsets between sensors using maximum-likelihood estimation. By registering different sensors spatially concerning each other, sensor fusion can easily eliminate spatial displacement. For the current usage of the robot, the Jaibot already has a reference sensor as the total station, it can achieve great accuracy, but with higher goals on eliminating errors to guarantee the quality of the product, extra sensors such as laser scanning could be adopted to catch these deviations.

Based on an interview with ALEC's representatives, the design change is a huge difficulty within the construction industry, specifically in Dubai and

surrounding regions. To solve this problem, updating the robot with real-time information of the construction site is necessary; thus, we can rely on digital twin construction (DTC) such as real-time updated BIM models. For example, Ye et al. [18] established a real-time interaction mechanism between digital design and physical construction. The design outcome is a dynamic, data-driven model, which would be updated by material conditions on-site. This could help the robot with real-time data instructions to guarantee the robot understands the design changes, which will reduce the effort and time on redesigning and rework.

4.1.2 Productivity

Based on our analysis, we notified that idle time takes the most time of the schedule. When refers to the industry partner's explanation, the Jaibot involved drawings and drawing approval. Without this in place and finalized, the work cannot continue, and since the Jaibot needs to be first in place, this also means that no other work can continue, which can cause major conflict between stakeholders. The work schedule overlap results in the current low level of efficiency. In the current practice, the schedule management framework is not yet generated by the project management team.

With a comprehensive structure of the schedule, it is easier to identify strategies to optimize the current workflow. Brosque et al. [3] analyzed the location-based schedule (LBS) and a 4D model to drill different areas and visualize how the robot impacted the continuity of crews working on production tasks, which successfully modeled the optimized schedule for robotic drilling.

Still, we figure out that with the long operation, the production rate seems to be at a higher level. This is because that continuous operation reduces extra effort to reset and calibrate the equipment, saving much time in the preparation stage.

4.1.3 Health and safety

The condition of the floor area greatly affected the drilling time and the safety of the operator and the robot. For example, when obstacles were present, "having to maneuver the robot around obstacles caused delays and [in some cases] collision, especially when navigating between different control points" (conversation with ALEC representative). Hilti, the robot manufacturer, also indicated that "Jaibot usually works in narrow corridors or spaces where there is heavy human traffic", and the "operator could have proximity to the robot during operation." Human activity on the job site could greatly influence the robot's stability, and in turn, the hazard could be brought to humans if the robot breaks at a certain distance from human beings. The project management framework should try to adapt to new regulations and rules for working with robots. Besides, a well-established

training program is needed. Continuous staff training can help address the various challenges and reduce false instructions because of human errors and mistakes

4.2 Human factor

4.2.1 Changing roles

Making the best use of humans and robots while keeping projects moving smoothly seems the biggest challenge when considering the changing roles in robotic adoption. Mossman [19] states that the on-site operation could greatly benefit from lean thinking, integrated project delivery (IPD), and BIM. The combination of such a strategy will support the just-in-time delivery of elements. It will improve productivity and efficiency via enhanced collaboration and integration.

4.2.2 Site culture

As defined in the site culture analysis, some construction companies face a shortage of technical workforce; thus, project managers should take a long-term view of workforce demand by simulating the future project pipeline. This forecast should be made on a granular skill-cluster level: it should consider, for example, future skills requirements in the digital space or the need for local market experts, but also expected productivity gains through technological advances. Companies should also engage constructively with the public sector to avoid misunderstandings, discuss the impact of regulations, and ensure good relations.

5 Robotic management framework

Based on the lessons learned from this case study, we summarized the basic structure of an integrated robotic management framework (Fig. 6) to implement an innovative system on the construction site. With

challenges and the optimization strategy identified in previous sections, a proposed framework was developed to assist owners, designers, CMs, and subcontractors to decide whether the new technology should be implemented or not and help with their future usage in other projects.

As shown in Fig. 6, CMs should develop the concept of the project first, and then by benchmarking the robotic applications, they need to define the activities where they would like to adopt robotic construction. In the planning phase, after initializing the contract, CMs will coordinate all parties to exchange technical profiles to understand the capacity of robots and overcome boundaries in specific tasks. CMs will also set up the work breakdown structure to allocate the tasks and develop an integrated management strategy to coordinate participants effectively. Designers and site managers can help with the schedule, budget, and quality management and develop reasonable ways for a robot to collaborate. All this information will be collected to generate an execution plan for a future test.

Before the actual implementation, digitalized models to simulate the robot's task can be used. Simulations are a cost-effective way to assess feasibility, safety, and cost risks in a real-world implementation. In the following step, during the testing phase, quantitative data such as task reports and qualitative ones such as people's attitudes could be gathered to test the feasibility of the robot. A comparison between robots and conventional working can help us better capture the efficiency of the robot. Information can then be used in the feasibility model. CMs' value on expectations of outcomes will help figure out what parameters to set up to evaluate the robotic system. Once the benefits and challenges are identified, all parties should work together to generate an optimization plan for further use or test. If the outcome is accepted, the robot application could then be adopted in a larger scope of the project.

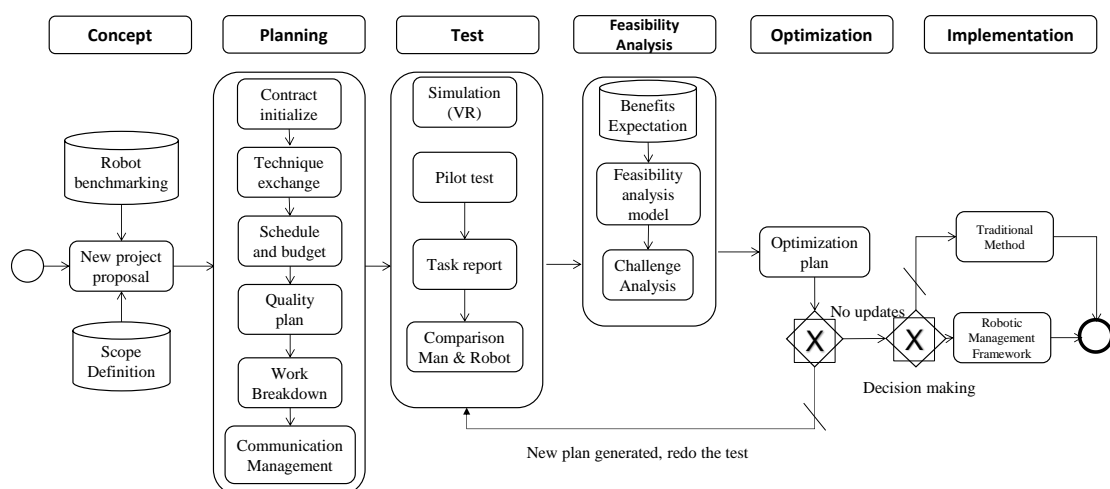


Fig. 6 Overview of the proposed robot adoption project management framework

6 Conclusions and Outlook

With the challenges identified in the previous feasibility analysis process, we proposed a framework to solve such problems and advance the current use of the Jaibot robotic system, which suggests the combination and integration of processes and technologies over the whole project management schemes to an advanced ecosystem of devices, equipment, resources, and workers.

Although the challenges are unique based on different robotic applications and different projects, the logic of using the feasibility analysis model to promote the framework set up a great foundation for investigating a generalized solution for robotic construction adoption. In the future, a more advanced framework with a state-of-the-art strategy will be added to push the future advancement of robotic construction applications.

For future studies, it is planned that the Jaibot might be used in other projects by ALEC; therefore, there could be opportunities for us to get firsthand data from the job site that could be used to further investigate the general management framework. Further studies could test the performance of this framework and advance it to a more general one. Besides, in future work, we will adopt a path correlation estimation and give different weights to the factors identified in the framework. That could help to understand how (and which) different factors influence robotic adoption.

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