Safety, quality, schedule, and cost impacts of ten construction robots

Cynthia Brosque1 · Martin Fischer1

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Abstract

Introduction Robots have increased productivity, quality, and safety in structured manufacturing environments while lowering production costs. In the last decade, advances in computing and sensing have started to enable robots in unstructured environments such as construction.

Objectives Given this new reality, this research aims to quantify the impacts of existing construction robots.

Methods This study evaluates the Safety, Quality, Schedule, and Cost impacts of ten on-site construction robots for 12 construction projects spanning 11 contractors from Europe, Asia, South America, and the United States.

Results The robots showed the potential to reduce repetitive site work between 25 and 90% and reduce time spent on hazardous tasks by 72% on average. On average, accuracy was improved by 55%, and rework was reduced by over 50%. Robots reduced the schedule on average 2.3 times with a median of 1.4x. The cost was reduced by 13%, with six cases that reduced it but four that increased the total costs. The comparative results also highlight under what project conditions (Product, Organization, and Process) could the robot perform better than the traditional method.

Conclusion Even at this relatively early stage of robot deployment worldwide, the consistent evaluation of ten examples showed how promising the technology already is for a range of robot types, mobility, autonomy, scale, business models, and locations. Future work will expand the number of robot case studies utilizing the same comparison method.

Keywords Robotics · Safety · Quality · Schedule · Cost · Case study

1 Introduction

Robots have been discussed in the construction industry since the late 80s, especially in Japan, when construction companies such as Obayashi and Shimizu developed robots to deal with growing personnel shortages. Recently, sensing, computing, and mapping technologies have allowed for robots in unstructured environments like construction.

Robots have increased safety and quality in the traditional manufacturing industry. Productivity, measured in value-added per worker, also increased by 3.0x (Andrews et al. 2016). However, on-site robots present added challenges compared to those commonly used in manufacturing. Construction robots must operate in highly unstructured, cluttered, and congested environments, surrounded by human workers (Saidi et al. 2016). Given these conditions, will construction robots obtain the same effect on productivity as in manufacturing?

As robotic construction methods for drilling, painting, bricklaying, reinforcing steel, and excavating tasks start being prototyped and adopted on-site, innovation leaders in construction must determine whether the robot will pay off, how it could pay off, and where to deploy it first. However, construction companies do not possess vast experience in robotics and therefore cannot count on historical data to assess the best option for any given project.

To attend this gap, previous work developed a Robot Evaluation Framework (REF) to guide innovators in construction companies looking to deploy robots in their projects (Brosque et al. 2021). We based the REF on a thorough literature review and three initial case studies that analyzed the performance of a concrete drilling robot (nLink), a drywall placing robot (Build-R), and a layout robot (Dusty Robotics) compared to traditional construction methods. To better understand the readiness of promising construction
robots, we expanded the scope of our study to ten additional cases. The cases included various project types and scales (commercial, residential, infrastructure) in several countries (Fig. 1). We also selected different robot types (multi and single-task robots, interior and exterior uses), tasks (e.g., material handling, finishing, reality capture, assistive, and layout), and business models (service and product).

This paper presents the Safety, Quality, Schedule, and Cost impacts of ten on-site construction robots compared to the traditional methods for selected construction projects. We highlight the site conditions and main resource assumptions for each case. Second, we reflect on the technology readiness and the forces acting for and against using robots in the construction industry.

The comparisons presented in this paper evaluate robots from the perspective of an innovator in construction looking to deploy an available robot solution for a given project. Other researchers have explored approaches for systems engineering of new single-task construction robots (Thomas et al. 2019; Hu et al. Jan. 2021) that could complement this comparative analysis.

2 Research method

We selected 11 contractors and 10 robots (Table 1) from seven countries: the US, Peru, Japan, Israel, Denmark, Switzerland, and Germany. The robots spanned from fully autonomous without human intervention to wearable assistive mechanisms. Interior and exterior robots with different mobility mechanisms included flying, four-legged, tracked, and wheeled robots with one-dimensional movement in the vertical or horizontal directions. We selected various form factors from large-scale tracked machinery to compact, easy-to-carry walking robots. Construction tasks spanned concrete drilling, wall finishing, layout, rebar tying, reality capture, material handling, hauling, and transporting scaffold materials. Four of ten cases were offered as services, three as products, and three as both a service and a product.

The construction projects included bridges, commercial buildings (community centers, warehouses, offices, data centers), oil and gas projects, and multi-family residential buildings.

Graduate students from Stanford University and the University of Lima picked industry partner matches consisting of a robot company and a GC. The students consistently analyzed the cases following the REF template composed of three main steps: (1) Analyzing the Product, Organization, and Process variables to determine the project’s feasibility and robot match. (2) Comparing the robot’s Safety, Quality, Schedule, and Cost to the traditional construction method.
(3) Finally, using a Decision Matrix with TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) Multi-Criteria Decision-Making method, students provided recommendations to the industry partners according to the project objectives (Fig. 2). At least two students analyzed all cases independently, except for cases #2 and #9, which were analyzed by one student each (Table 1).

The robot companies and GCs supplied quantitative and qualitative data during a 9-week evaluation period. Data consisted of Building Information Models (BIM), 2D plans, budgets, videos, pictures, industry standards, site measurements, scans, and access to interview key project and robot engineers. We collected additional data from exit interviews with the 19 industry partners and 19 students at the end of the evaluation process. Four participants did not complete the exit feedback.

3 Case study descriptions: robots and GC match

This section summarizes each case’s product, Organization, and Process (POP) considerations. It also highlights the main comparison assumptions like crew size, components, and site conditions.

4 DPR and HILTI

4.1 POP description

Jaibot (HILTI) is an interior concrete-drilling robot for installation hangers (Fig. 3). The robot requires an operator to move the robot between zones using a controller. Once in the correct zone, it autonomously drills all reachable holes for one or multiple subcontractors in one pass, marking holes with a unique pattern per subcontractor. The contractor rents the robot with a Hilti PLT 300 (digital...
Table 2  Product, Organization, and Process (POP) summary: Jaibot

| POP                               | Manual construction                                                                 | Robot                                                                 | Feasibility |
|-----------------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------|-------------|
| **Product**                       | Single: overhead concrete drilling                                                   | Single: semi-automated robotic drilling                              | OK          |
| Single/Multi-task                 | Interior                                                                             | Interior                                                             | OK          |
| Interior/Exterior                 | Drill, markers, lasers                                                                | Jaibot drilling system including Hilti TE-6A combi drill, VC-75 vacuum cleaner, controller, Hilti PLT 300 total station | OK          |
| Hardware                          | Walking and scissor-lift                                                             | Integrated tracked platform with vertical lifting                    | OK          |
| Mobility                          | Mostly manual                                                                        | Operator (hands-on, eyes-on) moves the robot between zones; in workstation, drills autonomously (hands-off, eyes-on) | OK          |
| Mechanization/Autonomy            | Manual for drill                                                                      | Tablet + joystick PLC 400                                            | OK          |
| Control interface                 | NA                                                                                   | Tilt sensors, stereo camera system for 3D vision, and speed controls | OK          |
| Software/sensors                  | Electricity                                                                          | Electricity, Wi-fi, Bluetooth                                       | OK          |
| Power/comms                       | Drill bits (12 mm)                                                                    | 1 drill bit preferred (set by anchor diam.)                         | OK          |
| Weight                            | 2323 m² (3 levels)                                                                   | 2323 m² (3 zones/level)                                            | OK          |
| Materials                         | Arizona                                                                              | Texas                                                                | OK          |
| Reach (workspace)                 | > 3 m                                                                                | Between 2.65 to 5 m (flat ceilings)                                 | OK          |
| Height (ceiling)                  | 4.3 m                                                                                | 4.3 m                                                                | OK          |
| Area                              | Drill bits (12 mm)                                                                    | 1 drill bit preferred (set by anchor diam.)                         | OK          |
| Location                          | Arizona                                                                              | Texas                                                                | OK          |
| Site conditions                   | Site elevator, low geometric complexity, usual obstacles                              | Elevator/crane to transport between levels, clear floorplate w/o obstacles preferred | OK – CIP required |
| # Units/zone                      | 1950 holes/zone                                                                       | 1950 holes/zone                                                      | OK          |
| Organization                      | Not applicable for AZ case                                                           | NA                                                                   | OK          |
| Types of skills and experience    | Trade experience, VDC coordination, and surveying                                    | Trades, VDC coordination, robot operation, Hilti support with digital layout/ training | OK, Hilti support |
| Labor supply                      | Sufficient                                                                           | Sufficient                                                           | OK          |
| Organization integration          | VDC coordination                                                                     | VDC and BIM coordinator                                             | OK          |
| # Organizations                   | 4                                                                                    | 5                                                                    | OK          |
| Stakeholders                      | 3 subs Mech, Electrical, Plumb (MEP)+ GC                                             | MEP, GC, robot (Hilti)                                              | OK          |
| Team experience in using robots   | The first time a project using this robot                                            | Deployed in several projects                                        | OK          |
| Process                           | Each sub drills and installs                                                         | The robot drills holes for all the subs at once                      | Link        |
| Process changes                   | Number of handoffs of information                                                    | Number of handoffs of information                                   | OK          |
| Data acquisition                  | BIM LOD 300, 2D plans                                                                 | BIM LOD 400 (with hangers/anchors)                                  | > LOD       |
| QC                                | Manual                                                                               | As-built QC, test holes for BIM alignment                           | OK          |
| Progress reports                  | Visual                                                                               | Automated progress report to the cloud w/dashboard. On-site progress transparency by marking pattern/trade | OK          |
layout total station), an integrated Hilti TE-6A combi drill, and a VC-75 vacuum cleaner. Hilti offers implementation and training services to the contractors (\* MERGEFORMAT Table 2).

Traditional overhead drilling is a strenuous task in noisy and dusty work conditions. We selected a 13,935 m², three-story, ground-up Healthcare Center project for Arizona State University in Phoenix, built by DPR. The concrete building with Cast-In-Place (CIP) slabs can use inserts or drill holes manually to place the installation hangers according to the BIM. Each trade independently occupies a project zone for manual drilling and hanger installation.

4.2 Case assumptions

The traditional project involved three crews: Mechanical, Electrical, and Plumbing, with combined productivity of 300 holes/day. The robot and operator can drill 500 holes/day. The number and density of holes and the number of drilling diameters significantly impact productivity—the traditional project involved 10,000 holes and one diameter. The case also assumed workers traditionally drilled overhead all the holes on the concrete slabs. However, the GC also commonly used slab inserts, which require a well-coordinated BIM to avoid coordinates mistakes as the robot process. This method would reduce the robot scope to 5% of reworked holes drilled after finishing the slab.

5 Obayashi logistics system

5.1 POP description

The Japanese construction company, Obayashi, developed an interior material handling robot collaborating with Stocklin. Material handling is a time-consuming and hazardous task (Fig. 4) that causes 15% of the yearly construction injuries reported in Japan (“Ministry of Health, Labour and Welfare” xxxx). Labor shortages also motivated the Obayashi Logistics System to reduce the workload transporting materials to the desired floor, typically part of Obayashi’s work scope (Table 3).

The Automated Guided Vehicle (AGV) can carry palletized materials, integrating with a custom elevator (that fits two AGVs) and an online logistics management system. The digital system replaces 68% of manually transmitted material orders. Following AGV ISO regulations, the robot detects humans with an on-board 2D Lidar scanner and reduces speed (at 50 cm) or stops if closer than 30 cm. Each AGV can handle pallets up to 1200 × 1800 mm. Unique materials, like ducts and pipes, are difficult to carry as they do not fit into a standard pallet size.

We studied this robot for an office building in Japan, for which the GC handled over 20 subcontractors’ materials.

5.2 Case assumptions

Traditional work considered a crew of five workers, and the robot work included the two AGVs with a robot operator and two crew members. In this case, Obayashi estimated an internal service cost per day plus the lease of the autonomous elevator. However, Obayashi also sells and supplies the robot as a service to other companies, estimating an investment break-even from external revenue in the next 5 years.

6 Bechtel and Kewazo

6.1 POP description

Kewazo, a Munich-based robotics and data analytics company, has developed “Liftbot” to assist the craft with the scaffold assembly tasks during construction (Fig. 5). The compact robot mechanically lifts scaffolding components vertically using a rail system mounted to the façade of the structure. The robot is semi-automatic with remote control, and workers load and unload the materials at both ends. The operator commands to start the operation by going up or down the façade. Future iterations will also incorporate horizontal mobility. “Kewazo Onsite,” a virtual platform, facilitates the work of the scaffolding administrator, tracking the site progress information.

We matched this robot to a 20-level, 40 m tall, 4440-piece scaffolding tower project from Bechtel (\* MERGEFORMAT Table 4). Traditional scaffolding involves transporting and assembling each component manually through a workers’ “chain line” at various heights until the material reaches the corresponding location according to the scaffold work order. The foreman records the hours and materials and submits them to the scaffold administrator, who computes the information in a scaffold management system. This labor-intensive process is repeated for each zone or level of work.
6.2 Case assumptions

The case assumed Liftbot worked on one scaffold project per month at $10,000/month, although the company stated they could have higher utilization levels. The traditional project deployed ten crew members, including a foreman and laborers of differing experience levels (hired locally on the U.S.), while the semi-autonomous robot only required four workers. The hourly labor rate for the project region was $55/h.
Table 4  Product, Organization, and Process (POP) summary Kewazo Liftbot

| POP | Manual construction | Robot | Feasibility |
|-----|---------------------|-------|-------------|
| **Product** | | | |
| Single/Multi-task | Single | Single | OK |
| Interior/Exterior | Exterior | Exterior | OK |
| Hardware | NA | Liftbot and rail system | OK |
| Mobility | Manual chain | Vertical movement along rails | OK |
| Mech/Autonomy | Low | Semi-automated control | OK |
| Control interface | Manual | Joystick (remote control) | OK |
| Software/sensors | NA | Camera-assisted image recognition | OK |
| Power and comms | NA | Battery | OK |
| Weight | 25 kg per piece (scaffolding) | 20 kg (robot) | OK |
| Site conditions | Multi-level scaffolding project | Install rail system (multi-level) | OK |
| Reach (workspace) | Chain-line by workers ∼ 2.5 m | ∼ 1 m² | OK |
| Height | 2 m per scaffold level (20 levels = 40.5 m) | No height limit, as long as the rail is installed | OK |
| Location | Pennsylvania | Germany | OK |
| Project type(s) | ECU pipe rack scaffold for cable tray access/installation | Industrial plants, construction sites | OK |
| # Units / zone | 222 pieces/level (4440) | 222 pieces/level (4440) | OK |

**Organization**

| Skills/experience | Scaffolding experience | Scaffolding experience, robot controls | OK |
| Labor supply | Labor sufficient for the project | Reduces labor resources | OK |
| Org. integration | NA | NA | OK |
| # Organizations | 3 | 4 | OK |
| Stakeholders | GC, scaffold specialist, supplier | GC, scaffold specialist, supplier, robot | OK |
| Experience w/robots | Drone experience | Over 30 projects | OK |

**Process**

| Process changes | Transport scaffolding manually | Lifts the scaffolding piece to desired level | OK link |
| # Handoffs of info | 11 | 14 | OK |
| Data acquisition | BIM and 2D plans | BIM and 2D plans | OK |
| QC | Manual/visual checks | Data analytics in platform: Kewazo onsite | OK |
| Progress reports | Manual (foreman records operation and hang tags to finish section) | Automated progress reports (online) | OK |

Fig. 6  Exyn robot system
7 Megacentro and Exyn

7.1 POP description

Exyn Technologies, a US-based company, has focused on autonomous aerial robot systems for GPS-denied environments, like mines. The fully autonomous, battery-powered drone scans a point cloud as it flies and swerves throughout unstructured, remote, and dangerous areas (Fig. 6). The sensing mechanism includes Lidar sensors, a thermal camera, and a scanner (Table 5). The system can also perform interior reality capture and 3D scans in the open to medium proximity to industrial environments. A hand-held alternative can reach closer proximity and integrate other interior robots such as Spot to fill in the gap of proximity scanning.

| Event type 0 | Surface layer erosion (preventive maintenance) |
|--------------|-----------------------------------------------|
| Material cost ($/m^2$) | 2 |
| Labor cost ($/m^2$) | 15 |

| Event type 1 | 3-layer coating erosion |
|--------------|-------------------------|
| Material cost ($/m^2$) | 12 |
| Labor cost ($/m^2$) | 15 |

| Event type 2 | 3-layer coating erosion and plate change |
|--------------|-----------------------------------------|
| Material cost ($/m^2$) | 76 |
| Labor cost ($/m^2$) | 15 |
| Plate change COST ($) | 200 |
| Plate area (m^2) | 2.6 |
| Plate length (m) | 2.2 |

Table 5 Event types and associated costs in the traditional inspection method

Table 6 Product, Organization, and Process (POP) summary: Exyn

| POP | Manual construction | Robot | Feasibility |
|-----|---------------------|-------|-------------|
| Product | | |
| Single/Multi-task | Multi: roof maintenance | Multi: reality capture and sensing | OK |
| Interior/Exterior | Exterior | Exterior/interior (medium proximity) | OK |
| Hardware | – | Drone, lidar scanner, camera | OK |
| Mobility | Human mobility | Flying | OK |
| Mech/Autonomy | Low | Auto (hands-off, eyes-off most ops) | OK |
| Control interface | NA | Laptop | OK |
| Software/sensors | NA | Multi-spectral sensor fusion, modular software | OK |
| Power and comms | NA | Battery-powered | OK |
| Weight | Worker (~70 kg) | 6 kg | OK |
| Clearance | Open and clear roof site | min 0.9 × 1.2 m | OK |
| Site conditions | Roof | Cleared for drone flight | OK |
| Height | 10.5 m | > 10 m | OK |
| Materials | lift, PPE | NA | OK |
| Area | 100,000 m^2 | 100,000 m^2 | OK |
| Location | Lima, Peru | US | OK |
| Project type(s) | Large-scale warehouse | Any open project | OK |
| # Units / zone | 1 (each building) | 1 (each building) | OK |
| Organization | | |
| Unions | Local unions present | Not enough info for this location | Review |
| Skills and experience | Inspection and height work | Robot software, inspection interpretation | Training |
| Labor supply | Sufficiently trained workers | Requires robot operator | OK |
| # Organizations | 1 | 2 | OK |
| Stakeholders | Megacentro | Megacentro + robot | OK |
| Team experience in using robots | None | Deployed in the US | OK |
| Process | | |
| Process changes | Yearly inspections employing people on roofs | Monthly autonomous drone inspections solve problems in a preventive way | OK |
| # Handoffs of info | 2 | 4 | OK |
| Data acquisition and types | Reports, pictures, and videos | Drone visualizes and delivers information in 3D for analysis | OK |
| QC | Manual | Automated, monthly | OK |
| Progress reports | Manual, labor subjective | Automated, objective (AI-based) | OK |
Exyn does not require any prior piloting experience as it can autonomously avoid obstacles and wires in cluttered environments while flying beyond line of sight. The maintenance team offloads the data using AI tools to interpret the collected input.

We selected a 100,000 m² warehouse in the district of Lurin, Peru. The warehouse owner, Megacentro, performs annual roof inspections with one operator skilled in working on heights over 10 m. This inspection can find three types of events (Table 6) with different maintenance requirements. Following the inspection, the worker identifies the event type and area affected, and the owner proceeds to fix the erosion.

### 7.2 Case assumptions

The drone can increase the frequency of the inspections (two revisions per month) to find the Event 0 type of issues that require preventive maintenance before the three layers of the coating erode. The Megacentro team estimated a 4.99% Event 1 erosion, 0.01% Event 2 erosion, and 1% Event 0 with the drone inspection frequency (Table 6).

### 8 Produktiva and SafeAI

#### 8.1 POP description

SafeAI has implemented autonomous driving for construction and mining (Fig. 7). Their service installs an AI interface of a drive-by-wire system, advanced sensors, an on-board computing platform, and autonomy software into a vehicle. Trucks, light vehicles, and heavy machinery, like skid steers, from any brand, become capable of performing tasks autonomously without a human operator inside the cabin. The system utilizes a preset path and a live environment analysis, including obstacles, people, and terrain conditions. Then, the operating system maps the task area and calculates a route with GPS data. A remote operator commands the vehicle to start, and the machine autonomously performs the task while generating a task report.

We evaluated SafeAI’s autonomous skid steer applied to a $6 M, 23-story residential construction project Alta, in Lima, Peru, by GC Produktiva. The project required hauling 700 m³ of material across 172 m. This project is relatively smaller than the usual infrastructure and mining projects completed with SafeAI (\* MERGEFORMAT Table 7).

#### 8.2 Case assumptions

A standard skid steer usually has two speeds: 11 and 20 km/h. So far, SafeAI has run at the lower tier speed for safety, while traditional operators drive at the highest speed. The results presented in this study considered the lower speed for the robot, although future iterations plan to deploy the same speed as the traditional operators. Additionally, one operator per autonomous machine was assumed, though the robot company expects to operate more than one machine simultaneously.

### 9 NCC and spot

#### 9.1 POP description

Boston Dynamics Spot is a quadruped robot for outdoor and indoor use (Fig. 8). The robot can traverse rough terrains, open doors with a robotic arm, and climb stairs. A tablet controller gives commands to the robot connected to a simple band or dual-band Wi-Fi for wireless communication. The construction industry has already deployed Spot to scan existing building structures, check the as-built state of the building against the BIM, safety control, and progress monitoring for invoice verification. Spot can repeat autonomously a pre-registered mission, which makes it suitable for repeat scans of the same zone as the project progresses.

The study focused on the structural and architectural scan of two existing floors (~ 8000 m²) in the Kineum project. The collaboration between NCC and Platzer planned to retrofit these two levels to add a 27-story hotel and offices to be completed in 2022.

Two workers scanned the two floors in 5 days in the traditional method. Both levels were filled with furniture and occupied during the scan. The area included 50 irregularly spaced small rooms, which required frequent equipment set-ups for each room. The multiple zones also mandated frequent stitching of the various scans in the point cloud (\* MERGEFORMAT Table 8).

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Fig. 7 Safe AI’s autonomous construction machinery

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| Table 7 | Product, Organization, and Process (POP) summary: SafeAI’s skid steer (Caterpillar 246D) |
|---------|----------------------------------------------------------------------------------|
| POP     | Conventional skid steer | Robot | Feasibility |
| Product | Single/Multi-task            | Single: load and dump | Single: load and dump | OK             |
|         | Interior/Exterior           | Exterior | Exterior | OK             |
|         | Hardware                  | Caterpillar 246D skid steer (operator seat, lift arm, bucket) | Skid Steer hardware parts (operator seat, lift arm, bucket), AI equipment (sensors and software) | OK             |
| Mobility | Tiers on CAT equipment (based on site conditions) | Same as conventional equipment | Same as conventional equipment | OK             |
| Mechanization/Autonomy | Medium: operator technical skills are required | Eyes-on, hands-off operation most of the task | Eyes-on, hands-off operation most of the task | OK             |
| Control interface | Control cabin with operator | Tablet controller for robot operator | Tablet controller for robot operator | OK             |
| Software/Sensors | Mechanical machinery | AI navigation, 360° sensors, Lidar, radar, camera | AI navigation, 360° sensors, Lidar, radar, camera | OK             |
| Power and communications | Fuel (gasoline) | Fuel (gasoline) and 100–300 kW to run the software and back-up battery | Fuel (gasoline) and 100–300 kW to run the software and back-up battery | OK             |
| Weight | 3368 kg | Same as the manual + the sensors and battery negligible weight | Same as the manual + the sensors and battery negligible weight | OK             |
| Clearance | Open path for loading and dumping | Open path for loading and dumping | Open path for loading and dumping | OK             |
| Site conditions | Open site with a defined path | Open site with defined path, connection (4G or 5G network) for the operation control station (OCS) | Open site with defined path, connection (4G or 5G network) for the operation control station (OCS) | OK, review terrain conditions |
| Reach(workspace) | 3 m upward and 0.7 m forward | 3 m upward and 0.7 m forward | 3 m upward and 0.7 m forward | OK             |
| Height | With lifting arm: 4.0 m Without lifting arm: 2.5 m | With lifting arm: 4.0 m Without lifting arm: 2.5 m | With lifting arm: 4.0 m Without lifting arm: 2.5 m | OK             |
| Volume (dirt) | 700 m³ | 700 m³ | 700 m³ | OK             |
| Location | San Isidro, Lima, Perú | Milpitas, Silicon Valley, California | Milpitas, Silicon Valley, California | Could import it |
| Project type(s) | Residential building | Construction, infrastructure, mining (large-scale preferred) | Construction, infrastructure, mining (large-scale preferred) | OK             |
| Number of units of work/zone | 172 m from loading to dumping Vehicle capacity: 0.8 m³/trip | 172 m from loading to dumping Vehicle capacity: 0.8 m³/trip | 172 m from loading to dumping Vehicle capacity: 0.8 m³/trip | OK             |
| Organization | Unions | Machine operators’ union | – | Review |
|         | Skills and experience | Certified skid steer operator | 3 weeks of training (3–6 mo. ideal) | OK             |
|         | Labor supply | High labor supply on skid steer operators | – | Other equip. have < supply |
|         | Organization integration | High-performance integrated team for earthworks phase | – | OK, integrate robot into Org |
| # Organizations | 2 | 3 | 3 | OK             |
| Stakeholders | GC (PM, supervisor), earthworks sub | GC (PM, supervisor, corporate executive), earthworks sub, SafeAI | GC (PM, supervisor, corporate executive), earthworks sub, SafeAI | OK             |
| Team experience in using robots | Semi-autonomous cranes | Several years of experience in field autonomous driving | Several years of experience in field autonomous driving | OK             |
| Process | Process changes | Determine pick-up and dump points | Similar sequence | OK             |
|         | Data acquisition and types | Manual | Initial mapping, GPS localization with sensors, and lidar radar camera | OK             |
|         | QC | Done by the supervisor and PM | Monitored remotely by the OCS and QC done by supervisor and PM | OK             |
|         | Progress reports | Manually done or not needed | Reports generated automatically | OK             |
9.2 Case assumptions

This case study analyzed a one-time scan. However, Spot provides the most benefits for repetitive scans (e.g., weekly scans of the same zone) and multi-sensor scans in one pass. None of the GC projects met these conditions, but NCC was interested in Spot because of their shortage of trained engineers to complete manual scans in their projects.

10 Swinerton, DPR, and canvas

10.1 POP description

The Canvas robot aims to support workers in interior drywall finishes, including mudding and sanding (Fig. 9). The robot consists of a mobile platform with an arm capable of using two end effectors: a sprayer to apply the drywall mud and a sander attached to a vacuum to smooth the surface. The robot has two LiDAR sensors to map and calibrate the workspace. Force sensing and compliance with the tools ensure a quality finish. The robot is mainly autonomous, requiring attention from the operator for 30% of the operation time. The operator controls the robot via a ruggedized tablet.

We paired canvas with GCs DPR and Swinerton, based in the Bay Area. Both companies build technical and commercial buildings with self-perform drywall arms. This organizational feature allows them to integrate Canvas, which operated as a subcontractor at the time of the study. The DPR pharmaceutical project included 5,935 m² of drywall finishing, broken into 11 zones of 186 m² each. Swinerton had already deployed Canvas at several small and medium-sized commercial projects. For the comparison analysis, we evaluated a 10,000 m² project. The manual process typically includes drywall hanging and finishing as part of the same scope.

10.2 Case assumptions

Depending on the size of a job, the Canvas team deploys a crew of five to seven drywall workers and one or two robots with an operator (trained by Canvas). Canvas employs union workers under District Council 16 for Bay Area projects like the conventional method. Traditional work for the task requires a similar crew size of five workers (Table 9).

11 HDlab and SuitX

11.1 POP description

Shoulder X is an exoskeleton developed by SuitX (MERGEFORMAT Table 10) to support skilled workers and reduce fatigue (Fig. 10). ShoulderX augments its wearer by reducing gravity-induced forces at the shoulder to perform chest to ceiling level tasks with less effort. The system balances the combined weight of the wearer’s arm and tool and quickly adjusts for different support levels and angles. An anthropometric profile and adjustable sizing allow for natural movement and intuitive awareness of the wearer’s position within tight spaces. The strength of the worker increases up to 80%, according to Engelhoven et al. (Engelhoven et al. 2018).

This study focused on overhead drilling for installation hangers from a Norwegian project by Kruse Smith, with over 1000 holes drilled manually (Brosque et al. 2021).

11.2 Case assumptions

We estimated the time to put on and take off the suit in about 5 minutes. The labor hourly cost was $43.75 in both scenarios. Finally, each $5,000 suit required a one-time training of $600.

12 Civ robotics and MT Højgaard

12.1 POP description

Civ Robotics, a site surveying and staking robot company from Israel with a base in the Bay Area, first created CivDrone, to autonomously place survey stacks by drone for large-scale energy projects, such as solar farms (Fig. 11). CivDot is a customizable wheeled form factor version performing the same functions with spray paint to layout points (Table 11). CivDot’s productivity and cost depend on (1) the distance between points and the total number of points, (2) the required accuracy, (3) site/terrain conditions, (4) battery life, and (5) spray paint or stakes layout. We centered on a three-wheeled model with 5-hour battery life, as it was...
the cheapest robot suitable for the selected project terrain and precision requirements. CivDot is preferred for dense and small commercial projects because of its size and safety compared to the six-foot drones. Its software facilitates the information exchange process and monitors task progress.

The Aquatics Cultural Center is a multi-level pool complex covering an acre of land built by GC MT Højgaard in Copenhagen. Complete with outdoor pool decks along the canals, the project requires placing 267 stakes around the island. Traditionally, two workers must obtain and upload
the point coordinates to a total station, clear the construction site, set up and calibrate the total station, and place the stakes manually.

12.2 Case assumptions

CivDot can place points to many different levels of accuracy, customizable for clients’ needs. For this project, the industry partners selected a lower accuracy level of ~15 mm with 1.5 mm repeatability. CivDot worked as a service as well as a product. Either option required a one-time training of $2000. The purchase price varied between $40,000 and $60,000 depending on the robot type. The GC opted to use the robot as a service because they could not predict future projects’ needs. The selected robot service was $4500/month with $300/month for maintenance.

The total number of points (267) was below average for the typical robot projects. Hence, additional calculations were made assuming a three-stage survey, with 200 points per stage.

13 TyBot by advanced construction robotics, impleenia, and traylor brothers

13.1 POP description

TyBot by Advanced Construction Robotics (ACR) is a single-task robot automating the ergonomically stressful bending over and tying rebar tasks (Fig. 12). TyBot can work through rainy, slippery conditions that pose labor safety hazards. Mechanically, it consists of a rigid manipulator mounted to a tram and rail system delivered to the project by towed trailer. The tram translates along a modular truss gantry mounted on adjustable legs set onto bogies with shaped wheels that drive the entire unit along screed rails. The set-up takes 30 min to 4 hours to configure on the first day. The robot supervisor (trained by TyBot in 6 days) inputs the desired rebar pattern, tying every or every other rebar intersection per structural specifications, and reloads the tie-wire. Once the support system is in place, the robot can start tying within 15 min.

For TyBot to be feasible several requirements of the rebar design and deck must be met as thoroughly specified by ACR (Robotics and “Rebar Equipment TyBot and IronBot”. xxx). TyBot is only compatible with horizontal rebar grids of at least 5.4×5.4 cm and not larger than a combined 17. The deck should be at least 900 m². Proprietary software runs TyBot with a wireless internet connection. The software and sensors (including a stereo camera system) map the ideal route, and the robot travels longitudinally between the two screed rails tying rebar intersections.

We assessed TyBot’s performance against two different projects (* MERGEFORMAT Table 12). The primary motivation to deploy TyBot in these projects was the shortage of skilled labor and the stagnant labor productivity (Garcia 2014). First, Impleenia’s SH4 Datacenter project in Switzerland installed 18,000 m³ of reinforced concrete slabs. The second project, a 1–10 Twin Span bridge in Slidell, Louisiana (U.S.) by Traylor Brothers, required 6–8 workers to complete the rebar of six spans in 6 weeks. An engineer specifies the structural rebar’s size, placement, overlap schedule, and bending requirements in such projects, but the ties and rebar joining methods are generally left to the steel installer. A team of ironworkers walks the horizontal rebar cage and, bending over, wraps and twists ties around the intersecting rebars. An owner inspector performs a final quality walk before pouring concrete.

13.2 Case assumptions

A data center was an unconventional application for TyBot, which focused on bridge projects. This scenario resulted in analysis nuances, like estimating the added costs for a temporary screed rail in the 25-m-wide data center and calculating obstacles impacts like columns and complex rebar cages. The student assumed the robot operator could navigate these obstructions with a moderate effect on productivity (from 1000 to 900 ties/h), but further data are needed to back up this assumption.

The students considered TyBot to work two 8-h shifts for the bridge project. The GC allocated a week per span for completion, which meant TyBot would only be active one or 2 days per week. TyBot recommends that the placement crew stay at least one shift ahead to minimize downtime.

TyBot was available for sale with a maintenance service contract. However, ACR stated that there is still not enough maturity in construction robotics to purchase the robot. Therefore, RaaS has been a valuable business model to showcase the technical capabilities at $3,600/week.
Table 9  Product, Organization, and Process (POP) summary: Canvas

| POP                               | Manual construction                  | Robot                                                                 | Feasibility |
|-----------------------------------|--------------------------------------|----------------------------------------------------------------------|-------------|
| **Product**                       |                                      |                                                                      |             |
| Single/Multi-task                 | Multitask: applying drywall compound (level 4 coat), sanding | Multitask: applying drywall compound (level 5 coat), sanding         | OK          |
| Interior/Exterior                 | Interior                             |                                                                      | OK          |
| Hardware                          | Mud mixer, drywall sander w/vacuum, bazooka | Robot arm (4 DOF) w/2 EE: spray painting nozzle & sander head        | OK          |
| Mobility                          | Manual                               | 4-wheeled platform                                                   | OK          |
| Mechanization/ Autonomy           | Low                                  | Semi-autonomous (eyes-on and hand-on to steer robot, hands-off once positioned) | OK          |
| **Control interface**            | Manual                               | Tablet                                                              | OK          |
| Software/sensors                  | –                                    | Lidar sensor (3D spatial mapping), vision sensors, rotary encoder    | OK          |
| Power and communications          | Electrical connection for drywall sander w/ vacuum | Battery (0.5 day), WIFI, electrical connection to charge             | OK          |
| Weight                            | All individual tool weigh < 0.9 kg   | 907 kg                                                              | OK          |
| Clearance                         | Open-floor layout                     | 1.2 × 0.8 m (robot dimensions) + 0.6-m clearance from walls (corners finished manually) | OK, w/ corner limits |
| Site conditions                   | Clear floorplate w/o obstacles, site elevator | Clear floorplate w/o obstacles preferred, site elevator             | OK          |
| Height                            | 3—5.0 m                              | 5.2 m                                                              | OK          |
| Materials                         | Mud compound, ladder, tape, stain-blocking primer, mud pan | Drywall compound                                                    | OK          |
| Area                              | 5935 m² of total wall area           | 5800 m²                                                            | OK          |
| Location                          | Bay Area, USA                        | SF, USA                                                            | OK          |
| Project type(s)                   | Commercial                           | Commercial                                                         | OK          |
| # Units / zone                    | 11 Zones of > 186 m² each            | 11 Zones of > 186 m² each                                           | OK          |
| **Organization**                  |                                      |                                                                      |             |
| Unions                            | Self-perform drywall sub (union workers) | Canvas Team (with DC16 union workers)                              | OK          |
| Types of skills and experience    | Taping, drywall compound application, and sanding experience | Taping, sanding, and robot operation experience                      | OK          |
| Labor supply                      | Sufficient supply                     | Break drywall scope + robot operator                               | OK          |
| Organization integration          | Medium (repeat drywall sub in several projects) | Long-term relationships with local contractors                 | OK          |
| # Organizations                   | 1                                    | 2                                                                  | OK          |
| Stakeholders                      | GC’s drywall self-perform sub        | GC, Canvas self-perform arm                                        | OK          |
| Team experience in using robots   | Have deployed layout and drywall robots in the past | Robot has been used on similar projects                              | OK          |
| **Process**                       |                                      |                                                                      |             |
| Process changes                   | Traditional application of soluble drywall compound in layers with drying downtime; vacuuming after sanding of each coat | Canvas team sprays 1-layer compound with robot arm followed by compliant sanding | OK see link |
| Data acquisition                  | 2D Plans and Specs                   | 3D Vision, 2D Plans, and Specs                                     | OK          |
| QC                                | Visual                               | Dual visual and automated QC (for thorough quality assurance)       | OK          |
| Progress reports                  | Visual                               | Automated                                                          | OK          |
This section summarizes the ten robots’ Safety, Quality, Schedule, and Cost impacts (Table 13). These impacts are relative to the traditional values provided by the GC partners for a particular project, as detailed in the previous section.

### 14 Comparative results: safety, quality, schedule, and cost impacts

Ethical and economic aspects of safety are critical motivators to adopt robotics (Kangari and Halpin 1989)–(Warszawski 1988). The construction industry is the third-highest fatal work in the U.S. (U.S. 2019), leading to social security and...
public health costs. In addition to fatal and nonfatal injuries, the physical strain is given by demanding work, ergonomically adverse postures, and adverse work conditions like noise and dust impact the length of workers’ careers and limit the influx of younger workers to the industry (Bock and Linner 2015). We organized the Safety impacts by robot types in the following categories: (1) interior single-task robots (STR), (2) Exterior STR, (3) surveillance and reality capture robots, and (4) wearable exoskeletons.

1) Interior STR

Interior single-task robots Canvas and Hilti focused on ergonomics and improving site conditions in repetitive
tasks working overhead and at heights. On the other hand, Obayashi’s robots focused on reducing site incidents. Canvas reduced manual finishing work at heights and prevented 95% of high dust concentrations from sanding tasks with over 150 mg/m$^3$ of dust particles, 10 × over the OSHA limit of 15 mg/m$^3$ (Miller 1997). Hilti’s robot observed similar benefits with an integrated dust removal system that absorbed the dust from concrete drilling. Moreover, it distanced the workers from the noise source of over 90 dB. Finally, according to the Japanese Safety and Health Department, Labor Standards Bureau, 15% (1,256 cases) of the injuries in Japanese AEC industries are related to material handling (2020–2021) (“Ministry of Health, Labour and Welfare” xxxx). Obayashi’s autonomous material handling robot can reduce these incidents to 0%.

2) Exterior STR

Exterior single-task robots include TyBot, Civ Robotics, Kewazo, and SafeAI. TyBot reduced 72% of the ergonomically challenging bending over tasks for rebar tying in a bridge project and 33% for the data center example with a more complex rebar layout. Kewazo and SafeAI focused on reducing the number of incidents while performing the task. Bechtel tracked that scaffolding erection and dismantling activities caused an average of 67 dropped-object incidents from 2018 to 2020, an average OSHA Incident Rate of 0.052. The robot reduced the number of dropped objects by 60–80%, automating the scaffold pieces’ transportation in the vertical direction. Finally, according to OSHA, heavy equipment in traditional construction is responsible for 75% of struck-by fatalities (U.S. 2019). The U.S. reports around 761 contacts with object and equipment-related deaths on construction sites per year. SafeAI has focused on site safety by removing the operator from the cabin. The robot performed more than 1000 cycles of work with no recorded incidents at the time of this study. The autonomous machinery case also observed opportunities to reduce the insurance rates by removing the workers from hazardous tasks. However, it was challenging to estimate the exact impacts without historical data to confirm the students’ assumptions.

3) Surveillance and reality capture robots

This category includes Spot and Exyn. Spot reduced to zero the 70% ergonomically challenging tasks of setting up reality capture equipment in the traditional method. Exyn replaced 100% of the dangerous and ergonomically difficult roof inspection activities by flying over the required area. The students observed potential insurance reductions by removing workers from heights and only requiring manual input to evaluate the collected data.

4) Wearable exoskeletons

The exoskeleton case focused on overhead injuries, specifically work-related musculoskeletal disorders (WMSD). According to the Bureau of Labor Statistics (“Back injuries prominent in work-related musculoskeletal disorder cases in 2016: The Economics Daily 2016), the shoulder was involved in 14.8% of all work-related musculoskeletal disorder cases reported in 2016 in the U.S. Workers who sustained a WMSD required 12 days before returning to work in 2015 (“Nonfatal occupational injuries and illnesses requiring days away from work 2015). Overall, as suggested by Everett (Everett 1993), construction robots are beneficial in tasks that require repetitive motions, large forces, and operations in hostile environments. However, the analyses relied on mostly broader statistical numbers, with few contractors estimating crisp incident numbers. Three challenges arose from the study of the ten robots: (1) safety data were not broken down in a way that was comparable to the robot task scope, (2) lack of readily accessible data by the GC (e.g., several subcontractors collected the data), and (3) safety impacts may not be detectable at the project level but on the long term instead, as with chronic damage.

Despite the difficulty of assessing injuries and changes in insurance rates, all the case studies could quantify the ergonomic impacts of robotics or qualitative benefits in the work conditions. The ten cases reduced on average 72% of the repetitive and ergonomically challenging work ranging from 25 to 90%. This percentage depended on the percent of work automated.
Beyond the safety and ergonomic benefits, the GCs expected that robots produced better or at least the same quality as traditional methods. As suggested by the construction robotics literature, the cases compared the accuracy and rework (Neil et al. 1993). Rework means redoing or correcting work thought of as finished. Depending on the task, rework entails not only man-hours but also material waste.
5) Interior STR

Interior single-task robots Hilti, Canvas, and Obayashi valued different quality sub-variables. Hilti’s Jaibot focused on drilling accuracy, which improved by 50% (6.35 mm to 3.17 mm). Canvas defined quality per Level of drywall finish from 1 to 5 and performed Level 5 drywall at the cost of traditional construction Level 4. However, their system required a different mudding process with 1.5 × material waste at the current stage of development. Finally, Obayashi focused on material handling rework using a management system that automatically controlled the robot’s operation according to the project schedule. This system reported a rework reduction from 3 to 1%.

6) Exterior STR

Exterior single-task robots TyBot, Civ Robotics, and Kewazo improved accuracy and reduced rework by 20–60%. TyBot adjusted the tension of the ties to help ensure tying quality. Rework, measured as the percent of bars not tied right the first time, lowered by 40% from 5 to 2.5–3%. Rebar obstructions caused the remaining rework, which had to be completed manually. Finally, material waste decreased from 2 to 0%. CivDot, from Civ Robotics, could place points to many levels of accuracy according to the client’s needs. For this project, 15-mm accuracy was sufficient with 1.5-mm repeatability, compared to the traditional 50-mm accuracy. CivDot could be outfitted with a second GNSS receiver at a higher cost if increased accuracy is needed. Furthermore, Civ Robotics’ reduced rework from an estimated 5% to 3%. Kewazo increased accuracy by 90% and reduced rework by 20%, from a traditional 32 to 26%. Rework causes were due to planning errors.

Finally, SafeAI provided an accuracy similar to the accuracy achieved by an operator in the cabin. However, the robot tracked the exact amount of material hauled, and the miles traveled.

7) Surveillance and reality capture robots

Spot achieved a 25% rework reduction from 20 to 15%, and Exyn achieved a rework reduction of 80% from 10 to 2%. The 10% represents the follow-up on the manual inspection. Both robots ensured consistent, repeatable data from multiple scans of the same space. Additionally, Exyn increased the roof inspection accuracy from 300 to 30 mm.

8) Wearable exoskeletons

Finally, exoskeletons estimated that fatigue reduction could lead to ~20% accuracy improvements, but further experimental data is needed to back up this assumption.

Overall, accuracy and rework were crucial variables to understanding the robots’ quality impact: all the robots but two increased task accuracy by 55% on average. Rework in traditional work ranged between 5 and 32% (with a 10% average). In two cases, there was not enough data to establish traditional rework. In two other cases, the REF entries relied on heuristics obtained through interviews but not accurately recorded. The site managers kept track of manual rework in the other six cases. In the robot cases, rework ranged between 0 and 25% (with a 5% average). In two cases, there was not enough data to document rework impacts. Half of the cases of robot rework due to human, context, or robot equipment errors required manual completion of the task. Finally, students also considered material waste and industry standards such as finishing levels in two instances.

17 Schedule

As indicated in Brosque et al. (Brosque et al. 2020), the ten cases analyzed the productivity of each robot to complete one unit of work, then one zone, and then the whole project.
1) Interior STR

STR improved the project schedules between 1.2x-2x according to the industry partners’ traditional resource and schedule estimations. Hilti’s 20% schedule reduction by drilling for the Mechanical, Plumbing, and Electrical subcontractors simultaneously follows the trend observed by a 2017 project completed by a prior version of this robot (Brosque et al. 2021). Canvas reduced the schedule by 2.0x with a new mudding technique that cut the drying time. Obayashi’s robot was designed to have the same productivity as the laborers. However, the site measurements showed it took 50% more time to carry the same amount of material with the robot due to a time increase in finding the materials. Hence, Obayashi’s team looked at combining the robot and human labor. Deploying a squad of two robots for the day and night shifts (with an operator) and two crew members only during the day achieved the same productivity as five workers during the day shift. This decision increased 68% the workers’ traditional daily capacity of 125 tons/day.

2) Exterior STR

TyBot reduced from six to two workers performing the same daily work. The traditional bridge project completed the ties in 113 days: 16 days per each of the six spans (2.66 h/span). TyBot estimated 11.6 8-h shifts to tie each span. The students also anticipated potential schedule reductions by working 16-h shifts. However, TyBot must follow one shift behind the iron placement team, so schedule efficiencies should consider the robot’s weekly utilization.

Kewazo took 78% longer to transport scaffolding materials on a unit-to-unit comparison. However, it required 40% of the traditional workers to complete the task, reducing the total labor time by 359.5 man-hours in a 20-level scaffolding project, according to data obtained through the Winter quarter of 2021. The students also considered that several Liftbot units could work together on one project to achieve faster erection schedules in the future. More recent tests showed that four workers with Liftbot were faster than a human chain of 8–10 workers considering the robot set-up and deinstallation (Newsdesk and “UK Scaffolders acquire first LIFTBOT robotic scaffolding hoists” 2022).

One exterior STR outlier was Civ Robotics which reduced the traditional schedule by 10.3x times. Under the project assumption for the layout of 600-points, the manual process took about 57 h with two workers and CivDot 5.5 h. CivDot relied on GPS and did not require extra set-up time to convey the information to the robot with minimum operator interventions.

SafeAI also showed a different trend in the schedule impact because it was pre-programmed to be slightly slower than the traditional operator as a safety measure. The company foresees that the performance could be the same as the traditional one in the future. Manual resources could reduce if one operator oversees several autonomous machines.

3) Surveillance and reality capture robots

Traditional roof inspection took 8 h manually versus 20 min with Exyn (a 24x reduction). The schedule was reduced by 1.6x for the first inspection, considering the coordination and repairs to deliver the finished roof. On the other side, Spot walked at a similar speed to the human worker and required a first manual walkthrough of the area before switching to an autonomous mode. The challenging indoor scanning conditions limited the robot’s speed, with over 50 rooms with clutter, obstacles, and human occupants. This environment, combined with the limited project scope without repetitive scans to take full advantage of Spot’s

| Table 14 | Cost and Schedule impacts of the ten robots |
|----------|------------------------------------------|
| Robot    | Task               | Int/Ext | Autonomy | Mobility | Cost (%) | Man/Rob Schedule |
| Exoskeleton | Assistive/Multi-task | Int      | Manual   | Human    | 73       | 1.1x             |
| Spot      | Reality capture    | Int/Ext  | Semi     | 4-legged | 24       | 1.0x             |
| SafeAI    | STR: hauling       | Ext      | Semi     | Tracks   | 13       | 0.7x             |
| Hilit     | STR: drilling      | Int      | Semi     | Tracks   | 6        | 1.2x             |
| Canvas    | STR: wall finish   | Int      | Semi     | Wheels   | – 8      | 2.0x             |
| TyBot     | STR: rebar tying   | Ext      | Semi     | Horizontal | – 29 | 1.8x             |
| Kewazo    | STR: material handling | Int/Ext | Human aid | Vertical | – 33 | 1.3x             |
| Obayashi  | STR: material handling | Int      | Semi     | Platform | – 41 | 1.7x             |
| Exyn      | Reality capture    | Int/Ext  | Autonomous | Air/modulara | – 51 | 1.6x             |
| Civ       | STR: layout        | Ext      | Semi     | Wheels   | – 84     | 10.3x            |
| Reduction | Median             |          |          |          | – 13     | 2.3x             |

aIntegration to a hand-held device or other robots
autonomy, could not achieve schedule benefits. However, Spot expanded the limited GC’s Virtual Design and Construction experts across different company projects.

4) Wearable exoskeletons

Finally, exoskeletons did not significantly impact the schedule as the wearable tool augmented the human worker but did not significantly modify the task’s productivity.

The Schedule impacts of the ten robots are summarized, filtered first by cost and second by schedule, based on the whole project comparison (Table 14). Overall, eight of the ten cases improved the schedule. One had the same traditional schedule, and one increased the schedule duration of the task under the traditional project production provided by the industry partners.

18 Cost

Finally, the cost to acquire advanced technologies and machinery in construction has been calculated with engineering principles such as the time value of money, cash flow analyses, and return on investment (Hu et al. Jan. 2021; Kangari 1985; Kumar et al. 2008). However, large amounts of capital are needed to develop, operate, and maintain robots which pose significant economic risks (Slaughter 1997). Hence, robot start-ups utilize a robots as a service (RaaS) model or rental/leasing options without requiring an initial investment and product maintenance from the GC.

The students contrasted the traditional material and labor hourly cost to the robot cost/m² or month, including any additional coordination time, training, or labor required to assist the task. Some robots could be purchased or leased, which made an essential component of the decision-making. The evaluators estimated a utilization rate based on the task demand for the project selected and estimated a depreciation period for the robot investment to aid this decision. We also considered business model changes. For example, the Canvas study broke down the traditional drywall cost between the wall installation and the finishes as the robot service only included the finishing scope.

Four of the ten cases were only offered as services and two as products. Three robots (CivDot, TyBot, and Exyn) could be used as a service or purchased, with one preferred deployment method (Table 15). Finally, Hilti was considered a product on a rental basis with a service cost for training.

This section describes the cost impacts of the robots offered as a product first and second, the impact of the service robots.

1. Product

The exoskeleton, Spot, and Exyn were offered mainly as a product. The least cost-effective was the exoskeleton because the students could not determine savings in health and safety due to incentives or insurance benefits. The wearable robot increased the cost by 73% with a $600/worker training and a one-time purchase of $5,000/suit. Second, the students observed that a project with repetitive scans or multiple scans in one pass was required for Spot to be cost-effective. The project selected for the Spot evaluation did not consider these constraints with a 5 day, one time pass scan that could not achieve cost benefits. Finally, Exyn achieved 51% cost savings compared to the manual method with labor and repair costs of $136,000/yr. In the robot scenario, the repair and labor costs are reduced to $17,000 due to the early detection of roof issues plus $50,000 of robot cost per project, considering a three-project annual utilization rate of ~10000 m² each. The payback for the drone investment was 1 year under the case assumptions. Finally, Hilti increased costs by ~6% compared to the traditional method with a labor rate of $30/h in Arizona for 1840 h, plus 72 h of coordination work between the subs. The robot cost included 437 labor hours, 72 h of coordination, and a monthly rental price of $15,000.

2. Robots as a service

The service category includes exterior and interior STR. Civ Robotics achieved the most significant cost impact in this category, cutting 84% of the traditional layout cost. CivDot was offered mainly as a service for $4500/month with a one-time training of $2000. The GC for the project chose the service option due to a lack of knowledge about future projects’ requirements and terrain characteristics.

TyBot achieved cost savings of 29%, considering a weekly service cost of $3,600 for the 1,982,064 m² bridge construction project and a traditional labor rate of $100/h.
Kewazo reduced costs by 33% with an estimated $10,000/month service by cutting down 360 man-hours (at an hourly rate of $55/h) for a 20-level scaffolding project in the U.S.

SafeAI was 13% more costly ($400 higher over 20 workdays) than the manual labor for the high-rise residential project in Lima, taking 14 days with a $22.6 man-hour hauling cost. The robot cost was $14/h plus $3/mile traveled and a $50 software fee. However, SafeAI’s current clients are large-scale mining, paving, and water infrastructure projects in the U.S, where the hourly cost is higher than the traditional residential Lima project.

Canvas improved costs by 8%, considering the weekly capacity of two robots working simultaneously on drywall finishing and their weekly price of 6.5 weeks.

Finally, Obayashi’s material handling robot achieved a 41% cost reduction using two robots simultaneously from $10.6/ton to $6.32/ton. The conventional material handling team of five workers costs $1,325/day. In comparison, the cost for a hybrid team of two crewmembers and two robots with an operator working both the day and night shift was $1,328/day, plus $12,000 per project for the autonomous elevator. However, the robot cut superintendents’ coordination needs by $188/day.

On average, the ten robots studied decreased total costs by 13%. Six of the companies achieved cost reductions: two between 0 and 30% (one interior and one exterior RaaS STR), three between 30 and 60% (one interior and one exterior RaaS STR, and one interior exterior reality capture robot), and one between 60 and 90% (an exterior RaaS STR). On the other hand, four robots increased the cost of the traditional task: three between 0 and 30% (one interior RaaS STR, one exterior RaaS STR, and a reality capture robot product) and one over 60% (a wearable exoskeleton product).

19 Discussion

This section reflects on the technology readiness and the forces acting for and against the use of robots in the construction industry based on the comparison results and the exit interviews with the industry partners and students involved in these case studies.

Even though construction robots in the field are in infancy in their deployment worldwide, these examples showed how promising the technology already is for a range of robot types, mobility, autonomy, scale, business models, and locations. The students and industry partners agreed that the technology was highly ready or somewhat ready, with no participant indicating the robots were not ready for deployment. One Peruvian GCs stated that “[they] thought it was more expensive. […] its adoption is closer than we think. However, it is important to analyze the alternatives early.”

Participants identified forces acting for robots in construction, such as construction’s need to optimize productivity and costs, the safety culture in construction that incentivizes solutions that distance workers from dangerous tasks, and labor shortages. Other forces highlighted were available technology, quality requirements, willingness to adopt the technology, increased project complexity, and COVID-19 restrictions.

On the other side, the forces acting against robot adoption comprised resistance to change, cost of deployment and training effort, unpredictable site conditions, process changes, lack of information about robots’ capabilities, technology not sufficiently mature to buy out of the box solutions, lack of robot adaptability to the construction and design conditions, contract changes, and lack of suppliers (e.g., in South America).

Aggregating the results from the ten cases using the REF allowed us to compare data about different types of robots. We observed a preference for RaaS versus products and a limited autonomy from the on-site robots, which require a human operator nearby on a 1:1 basis. Future efficiencies could be achieved from a 1: many model. The robots under study still have limitations such as accessibility, battery life, communication with other systems, and the timing of design decisions.

20 Conclusions

This paper presented a summary of the Safety, Quality, Schedule, and Cost impacts of ten robots for real construction projects and showed that five of the ten robots were better than the traditional method for all four categories. A preliminary step of the study established the feasibility of each project and robot match considering the Product, Organization, and Process variables.

The comparative results showed that companies should track safety and costs in an accessible way to make automation decisions. Issues like chronic damage to workers were difficult to capture accurately and precisely in most cases. All robots except for two increased traditional task accuracy by 20 to 90% (55% on average), and the robots reduced rework by over 50% compared to the conventional methods. The schedule improved on average 2.3x, with eight cases that improved it, one that increased it, and one that remained the same. The median was 1.4x, about half of the manufacturing robots’ effect on productivity (3.0× increase) (Andrews et al. 2016). A key reason for this reduced schedule impact is that robots did not completely replace the workers but served as a tool to support or augment the workforce in risky or repetitive tasks. The reality capture drone (Exyn) was the only robot that could perform autonomously without human
intervention. The cost analysis showed six cases in which the robots increased the traditional cost, and four reduced it. We also observed different business models for adopting robots as a service or product. Product offerings required a known yearly utilization of the robot to offset a higher initial investment, which was difficult to estimate by the GCs. Only one of the product robots (autonomous drone) reduced the costs under the traditional project assumptions. Leasing or service models allow for added flexibility and simplify the cost comparison against manual labor rates.

Finally, we ought to note that all the robots included in the study are still developing and improving as they gather feedback from pilot projects in sites worldwide. The results presented in this paper reflect performance data obtained through the winter quarter of 2021. Hence, having a framework in which we can quickly update new values to Safety, Quality, Schedule, and Cost is essential to evolving the construction understanding of the value proposition of each robot. This study compared the SQSC of robots under one set of project data and assumptions provided by the construction industry partner in each case. The comparative results highlighted under what project conditions the robot could perform better than the traditional method.

Our ongoing work is expanding the number of projects and robots case studies with this comparison method, sensitizing variables such as labor rate, indirect costs, robot service cost, and project size to address which assumptions are most impactful for robot adoption. This effort focuses on building and keeping a database of construction robots with a blueprint of a repeatable analysis method between robots and GC industry partners. The framework template is available to download from the repository ‘REF.git’ at https://github.com/cbrosegue/REF.git.

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Declarations

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

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