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REVIEW

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

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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 80 s, 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

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Fig. 1 Industry partners global distribution including robots and construction companies

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.

Table 1 Case studies robot and GC match

#	GC	Robot
1	DPR	Hilti concrete drilling
2	Obayashi	Material handling (Obayashi)
3	Bechtel	Kewazo scaffolding
4	Megacentro	Exyn autonomous drones
5	Produktiva	SafeAI
6	NCC	Boston dynamics spot
7	Swinerton	Canvas drywall finishes
8	DPR	Canvas drywall finishes
9	HDlab	SuitX
10	MT Højgaard	Civ robotics
11	Implenia	TyBot
12	Traylor Brothers	TyBot

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.

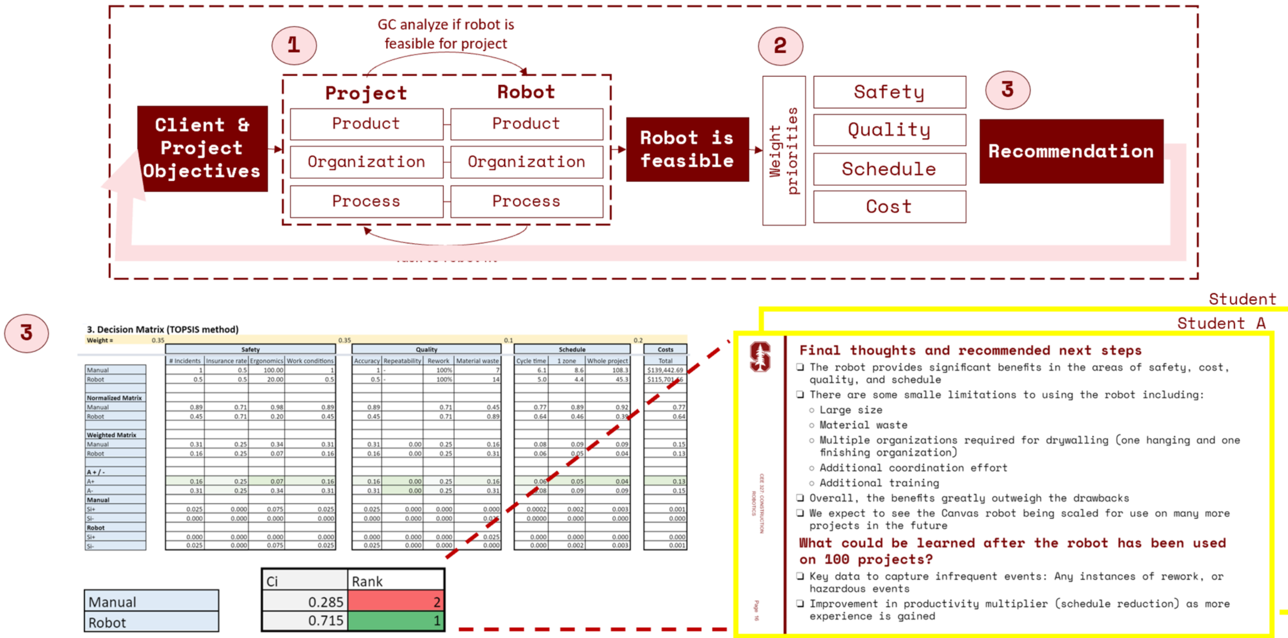

Fig. 2 Evaluation method broken down in three main steps: (1) Product, Organization, and Process feasibility; (2) Safety, Quality, Schedule, and Cost; (3) Recommendations based on the client and project objectives

(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.

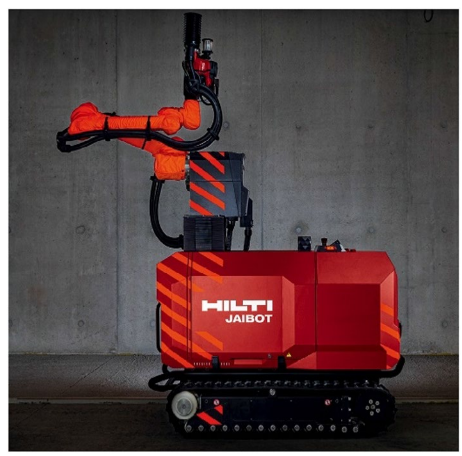

Fig. 3 Hiliti's Jaibot concrete drilling robot

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/Multi-task	Single: overhead concrete drilling	Single: semi-automated robotic drilling	OK
Interior/Exterior	Interior	Interior	OK
Hardware	Drill, markers, lasers	Jaibot drilling system including Hilti TE-6A combi drill, VC-75 vacuum cleaner, controller, Hilti PLT 300 total station	OK
Mobility	Walking and scissor-lift	Integrated tracked platform with vertical lifting	OK
Mechanization/Autonomy	Mostly manual	Operator (hands-on, eyes-on) moves the robot between zones; in workstation, drills autonomously (hands-off, eyes-on)	OK
Control interface	Manual for drill	Tablet + joystick PLC 400	OK
Software/sensors	NA	Tilt sensors, stereo camera system for 3D vision, and speed controls	OK
Power/comms	Electricity	Electricity, Wi-fi, Bluetooth	OK
Weight	< 1 kg Hilti drill	820 kg	OK
Clearance	Open-floor layout	82 × 160 cm	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
Reach (workspace)	> 3 m	Between 2.65 to 5 m (flat ceilings)	OK
Height (ceiling)	4.3 m	4.3 m	OK
Materials	Drill bits (12 mm)	1 drill bit preferred (set by anchor diam.)	OK
Area	2323 m^2 (3 levels)	2323 m^2 (3 zones/level)	OK
Location	Arizona	Texas	OK
Project type(s)	Health care	Any large-scale commercial	OK
# Units/zone	1950 holes/zone	1950 holes/zone	OK
Organization			
Unions	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			
Process changes	Each sub drills and installs	The robot drills holes for all the subs at once	Link
Number of handoffs of information	5	3	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 m^2, 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).

Fig. 4 Obayashi and Stocklin AGV material handling robots

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.

Table 3 Product, Organization, and Process (POP) summary: material handling robot

POP	Manual	Robot	Feasibility
Product			
Single/Multi-task	Transport material	Single task	OK
Interior/Exterior	Interior	Interior	OK
Hardware	Hand pallet truck/Forklift	Robot (2D-scanner, pallet lift, mobility unit)	OK
Mobility	Foot	Small wheels	OK
Mechanization/Autonomy	Low	Autonomous (hands-off)	OK
Control interface	Manual	Material handling app	OK
Software/sensors	–	Bluebotics program	OK
Power/communications	–	200 V AC / On-site WIFI	OK
Weight	–	1000 kg	OK
Clearance	1000 mm	500 mm	OK
Site conditions	Flat and clean floorplate	Flat and clean floorplate/custom lift Max. slope 4 cm	Auto lift, steps require ramps
Reach (workspace)	Any pallet	Pallets up to 1200 × 1800 mm	Restrictions
Height	> 2 m	1938 mm	OK
Materials	–	–	OK
Area/total work	31,250 t	31,250 t	OK
Location	Tokyo	Tokyo	OK
Project type(s)	Office	Any large-scale building	OK
Units of work/zone	125 t/day	at least 125 t/day	OK
Organization			
Unions	NA	NA	OK
Types of skills and experience	Muscle power/ Safety detection	Computer experience, one robotics manager	OK
Labor supply	Limited	Requires only 1–2 crewmembers	OK
Organization integration	–	–	OK
# Organizations	2 + ~ 20–30 subs	2 + ~ 20–30 subs	Depends # subs
Stakeholders	GC, material handling labor, subs	GC (including robot), material handling labor, subs	
Team experience in using robots	None	Not necessary to operate a robot / use the app	OK
Process			
Process changes	Super coordinates directly with labor	Super uses management app for work orders	OK
Information handoffs (#)	16	14	OK
Data acquisition & types	Oral and document instruction	Oral instruction and management app	OK
QC	–	–	OK
Progress reports	Oral & direct observations	Push notice and direct observations	OK
Detailed workflows	Link	Link	OK

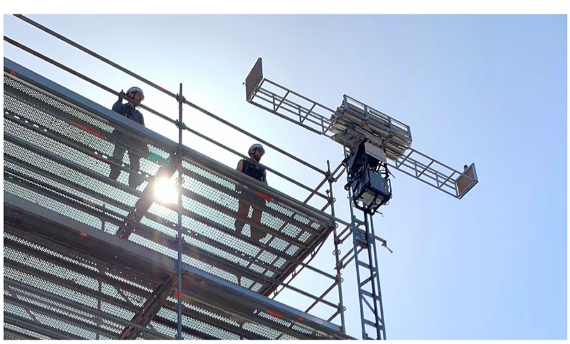

Fig. 5 Kewazo's Liftbot scaffolding assembly robot

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 m^2	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

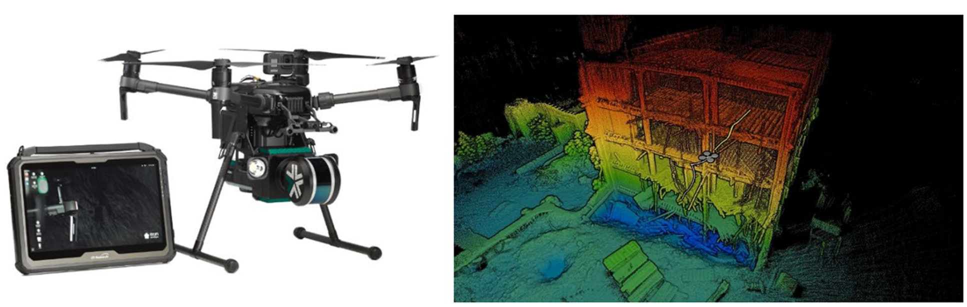

Fig. 6 Exyn robot system

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

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

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.

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 m^2 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

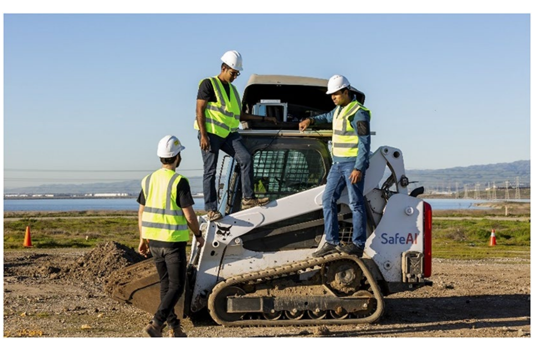

Fig. 7 Safe AI's autonomous construction machinery

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 m^3 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 m^2) 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).

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	OK
Mechanization/Autonomy	Medium: operator technical skills are required	Eyes-on, hands-off operation most of the task	OK
Control interface	Control cabin with operator	Tablet controller for robot operator	OK
Software/Sensors	Mechanical machinery	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	OK
Weight	3368 kg	Same as the manual + the sensors and battery negligible weight	OK
Clearance	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)	OK, review terrain conditions
Reach(workspace)	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	OK
Volume (dirt)	700 m^3	700 m^3	OK
Location	San Isidro, Lima, Perú	Milpitas, Silicon Valley, California	Could import it
Project type(s)	Residential building	Construction, infrastructure, mining (large-scale preferred)	OK
Number of units of work/zone	172 m from loading to dumping Vehicle capacity: 0.8 m^3/trip	172 m from loading to dumping Vehicle capacity: 0.8 m^3/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	OK
Stakeholders	GC (PM, supervisor), earthworks sub	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	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

Fig. 8 Boston Dynamics' Spot reality capture robot

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 m^2 of drywall finishing, broken into 11 zones of 186 m^2 each. Swinerton had already deployed Canvas at several small and medium-sized commercial projects. For the comparison analysis, we evaluated a 10,000 m^2 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

Table 8 Product, Organization, and Process (POP) summary: Spot

POP	Manual construction	Robot	Feasibility
Product			
Single/Multi-task	Single: 3D scanning for progress monitoring	Multi-sensor reality capture	OK
Interior/Exterior	Interior	Interior and exterior	OK
Hardware	BLK 360 from Leica	Spot and Lidar	OK
Mobility	Walking	4 legs (access what humans can)	OK
Mechanization/Autonomy	None	Operator present for first walk, then autonomous	OK
Control interface	Control pad Leica	Computer OR control pad	OK
Software/sensors	3D scan	Proximity and depth sensors, camera, 3D scan	OK
Power and communications	–	Bluetooth, Wi-Fi, LTE, battery + recharge station	OK
Weight	~ 10 kg	~ 35 kg	OK
Clearance	Any space a human can access	50 × 110 × 70 cm	OK
Site conditions	Existing building scan required	No special requirements	OK
Reach (workspace)	Human reach	Carrying capacity kg: 14, arm 11	OK
Area	8,000 m^2 (2 levels)	8,000 m^2 (2 levels)	OK
Location	Sweden	Boston	OK
Project type(s)	Commercial building	Any	OK
# Units / zone	8 zones of 1,000 m^2 (50 rooms total)	8 zones of 1,000 m^2 (50 rooms)	OK
Organization			
Unions	Workers' protection in Sweden	NA	OK
Skills and experience	Surveying, VDC	VDC, robot operation	OK
Labor supply	Limited supply of VDC professionals to meet project demands	Can be walked by construction workers	OK
# Organizations	1	2	OK
Stakeholders	GC (VDC team, surveyor)	GC (VDC, surveyor) + robot	OK
Team experience in using robots	None	Deployed it in several projects around the world	OK
Process			
Process changes	Scan each zone manually with frequent set-ups per room	Set up scanning route w/robot operator, repeat autonomously	Repeat scans preferred
# Handoffs of info	2	3	OK
Data acquisition	3D Scan, BIM	3D Scan, BIM	OK
QC	Manual post-processing of scans	Consistent post-processing	OK
Progress reports	Not available	Robot route report	OK
Comments	No barrier to robot implementation	A one-time scan does not take advantage of the full autonomy	Review SQSC benefits

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

Fig. 9 Canvas drywall finishing robot

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, implenia, 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". xxxx). 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 m^2. 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, Implenia's SH4 Datacenter project in Switzerland installed 18,000 m^3 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	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 m^2 of total wall area	5800 m^2	OK
Location	Bay Area, USA	SF, USA	OK
Project type(s)	Commercial	Commercial	OK
# Units / zone	11 Zones of > 186 m^2 each	11 Zones of > 186 m^2 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 checks	Automated	OK

Table 10 Product, Organization, and Process (POP) summary: SuitX

POP	Manual construction	Exoskeleton	Feasibility
Product			
Single/Multi-task	Multi-task	Multi-task	OK
Interior/Exterior	Interior and exterior	Interior and exterior	OK
Hardware	Drill, laser, ladder	Drill, laser, ladder, exoskeleton	OK
Mobility	Manual	Manual	OK
Mechan/autonomy	None	Low (assistive)	OK
Control interface	Manual	Manual	OK
Power and comms	NA	Battery-powered	OK
Weight (kg)	Drill < 1	Drill < 1, exo = 3.2	OK
Clearance	Open-floor layout	Any place a human could access	OK
Reach	Manual	Human height	OK
Project type(s)	–	–	OK
# Units / zone	–	30 min of use	OK
Organization			
Unions	Present for the selected task	Unions can push the adoption	OK
Skills and experience	Overhead skills for the task	Training in using and adjusting exo	Extra time
Labor supply	Supply of skilled workers sufficient	Augments traditional crew	OK
Org. integration	-	None, HR potential integr. strategy	OK
# Organizations	> 2	> 2 (depends # subs using exo)	OK
Stakeholders	Management, QHSE, Construction Foreman, Supervisors, and Sub	Management, QHSE, Construction Foreman, Supervisors, and Sub	OK
Robot experience	No experience in using exoskeletons	Limited applications on-site so far	OK
Process			
Process changes	Strenuous overhead drilling	No changes, augment workforce	OK
QC, data types	Manual, 2D plans	Same as traditional	OK
Progress reports	Manual	Same as traditional	OK

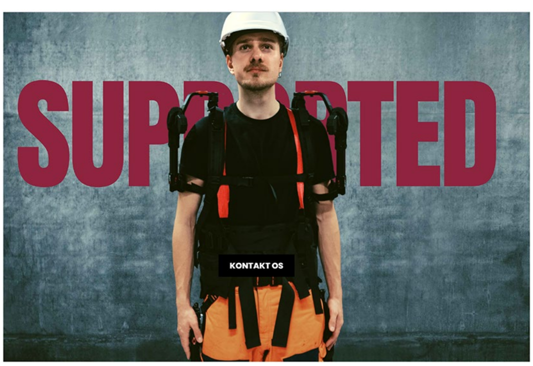

Fig. 10 Shoulder X (version 3.0) by SuitX

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

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

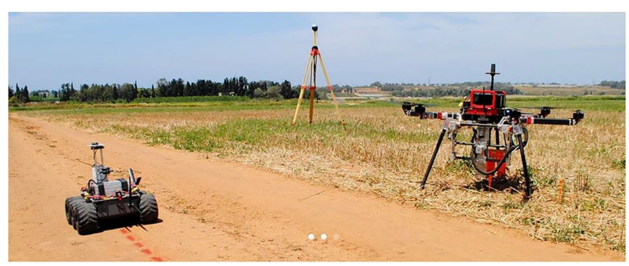

Fig. 11 CivDrone and CivDot exterior layout robots

for a particular project, as detailed in the previous section.

15 Safety

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

Table 11 Product, Organization, and Process (POP) summary: Civ Robotics

POP	Manual construction	CivDot	Feasibility
Product			
Single/Multi-task	Single: site Layout Survey/Staking	Single: site Layout Survey/Staking	OK
Interior/Exterior	Exterior	Exterior	OK
Hardware	Total station, stakes	CivDot robot product	OK
Mobility	By foot	Three small off-road wheels	OK
Mechanization/ autonomy	Low	Operator to monitor progress and service robot when necessary (eyes-on hands-off most time)	OK
Control interface	Total station controls	Tablet / PC	OK
Software/Sensors	Reference points for total station	GPS	OK
Power and comms	Electricity/battery for total Station	Battery for Robot (~5 h), GNSS RTK	OK
Weight	N/A	18 kg	OK
Clearance	N/A	1×0.4×0.7 m	OK
Site conditions	Adequate visibility, leveled ground, free of large debris	Leveled ground, free of large debris, typical weather except frozen ground	OK
Reach	Any	Up to 8 km from base station	OK
Materials	Stakes/flags	Spray paint/stakes	OK
Area	Full site of ~2700 m^2 (267 points)	600 points recommended	Project scale
Location	Copenhagen, DK	Bay Area, USA	OK
Project type	Aquatics Center	Large projects with a high # of stakes	OK
# Units/zone	267 points	3 zones of 200 points	OK
Organization			
Unions	Unions involved in Denmark	Not enough info	Review req
Types of skills and experience	Total station calibration, surveying	Robot operation, export site survey data to the robot	OK
Labor supply	Adequate	Reduce specialized labor	OK
Org. integration	High (VDC)	N/A	OK
# Organizations	2	3	OK
Stakeholders	MT Højgaard, Municipality of Copenhagen	CivRobotics, MT Højgaard, Municipality of Copenhagen	OK
Team experience in using robots	No prior exposure	Deployed in several projects and can train operators to use robot within hrs	OK
Process			
Process changes	Upload file to total station, mark points with stakes/flags manually	Provide data to the robot management software; points placed automatically	OK
# Handoffs of info	4	3	OK
Data acquisition and types	2D plans, total station CSV points	Can customize for customer (e.g., csv, dxf, CAD file)	OK
QC	Manual check of coordinates	Review 5 coordinates each day to check the calibration	OK
Progress reports	Manual/Visual	Automated report generation/day via management software	OK

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

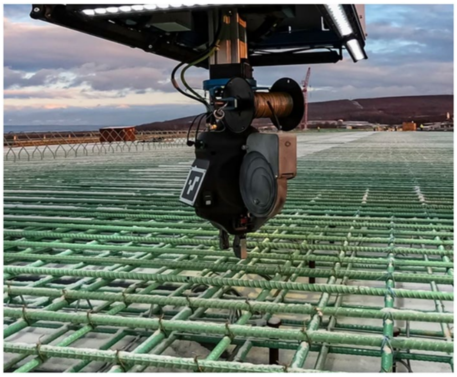

Fig. 12 TyBot rebar tying robot

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.

Table 12 Product, Organization, and Process (POP) summary: TyBot

POP	Manual construction	Robot	Feasibility
Product			
Single/Multi-task	Single: rebar ties	Single: autonomous rebar tying	OK
Interior/Exterior	Interior/Exterior	Interior/Exterior	OK
Hardware	Rebar ties, pliers	TyBot, gantry frame, and legs	OK
Mobility	Walking, bending over	Moves on tram, requires rail system structure	OK
Mech/autonomy	None to low	Once set up hands-off, eyes-on	OK
Control interface	Manual	Some remote controls	OK
Software/sensors	None, visual inspection	AI and sensors to recognize rebar/intersection	OK
Power and communications	Battery-powered tying tools may be used	Generator	OK
Weight (kg)	0.68	2926	OK
Clearance	Standing on rebar cage	Details summarized in text description	OK
Site conditions	Any slab rebar under the right weather	Rainy, wet operation under specified size restrictions	OK
Reach (workspace)	Human bent over, arm's length	Once set up, will reach all rebar ties	OK
Height	N/A	Details summarized in text description	OK
Materials	Rebar ties, rebar cage to be tied	Rebar ties	OK
Area	18,000 m^3(Implenia)/6 span bridge	18,000 m^3 (Implenia)/6 span bridge	OK
Location	Switzerland (Implenia)/US (Traylor Brothers)	Pittsburgh (US) based company (East Coast projects mainly)	OK
Project type(s)	Datacenter (Implenia), Bridge construction (Traylor Brothers)	Mainly bridges over 900 m^2	OK
# Units/zone	1 span	up to 1000 ties/h	OK
Organization			
Unions	Ironworkers or laborers' unions	Collaboration with local workers	OK
Types of skills and experience	Ironworkers' skills are highly variable across projects	6 days of training for a contractor to run TyBot	OK
Labor supply	Shortage of skilled labor – crews typically need rebar reinforcement	Labor shortage is a key motivation	OK
Organization integration	Medium to low level of integration	GC may integrate TyBot on several feasible projects in the pipeline	OK
# Organizations	3	4	OK
Stakeholders	GC, Ironworkers, or laborers, QC Owner's rep inspectors	GC, Ironworkers or laborers, Tybot, QC owner's rep inspectors	OK
Robot experience	Limited to none	> 25 projects (by end 2020)	OK
Process			
Process changes	Rebar cages are laid out and tied manually at specified intersections	Review project info, set up screed rails, transport and install robot, execute ties autonomously	OK
# Handoffs of info	4	6	OK
Data acquisition	Work order details, 2D plans	Work order details, 2D plans	OK
QC	Visual inspection of rebar intersections (inspector); may trigger rework of ties	TyBot checks quality; inspector double-checks ties	OK
Progress reports	Not available	Logs task performance analysis (active h., # ties, # ties tried & skipped)	OK

16 Quality

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.

Table 13 Summary of comparison impacts[a]

	Reduction	Comments
Safety	72%	Repetitive work was reduced in all cases by 25–100%
		Only 4 cases could quantify the impact of incidents and insurance rates
Quality	55% accuracy	Accuracy was improved by 55% on average, with a range from 20 to 90% 2/10 cases could not quantitatively assess accuracy improvements
	> 50% rework	Traditional rework ranged from 5 to 32%
Schedule	2.3x	8 reduced
		1 remained the same 1 increased
Cost	13%	6 reduced costs
		4 increased

[a]Average reductions are relative to traditional values provided by GC partners

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-2 × 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 2.0 × 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 crewmembers 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 10.3 × 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 24 × reduction). The schedule was reduced by 1.6 × 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
Hilti	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/modular[a]	− 51	1.6x
Civ	STR: layout	Ext	Semi	Wheels	− 84	10.3x
				Average	− 13	2.3x
Reduction				Median	− 19	1.4x

[a]Integration 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/m^2 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.

Table 15 Robot classification between service and product offer

Robot	RaaS	Product
Exoskeleton		X
Kewazo	X	
Obayashi	X	
SafeAI	X	
Hilti	Training service	X (rental)
Canvas	X	
Civ Robotics	X[a]	X
TyBot	X[a]	X
Spot		X
Exyn	X	X[a]

[a]Scenario analyzed for this project

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 m^2 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 m^2 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 US, 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/cbrosque/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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