Evaluation of an Autonomous Driving Dumper using a Robot Evaluation Framework

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Abstract

This paper evaluates the applicability of an autonomous driving dumper for a construction project. Conducted as part of a joint lecture between Stanford University and the Technical University of Munich in 2024, this study provides students with hands-on experience in field assessments of construction robotics. The dumper, developed in partnership between the Technical University of Munich and the industry partner Wacker Neuson, is analyzed using the Robotics Evaluation Framework. Autonomous dumpers present a promising solution in the construction industry, offering improved safety, productivity, and the ability to address labor shortages, particularly on small and confined sites. The Robotics Evaluation Framework used is a systematic methodology for assessing feasibility and performance across safety, quality, schedule, and cost metrics. The results demonstrate that the autonomous dumper improves safety through better ergonomics, enables operators to focus on higher-value tasks, and enhances overall efficiency. While quality remains comparable to conventional dumpers, the autonomous system experiences 20% longer cycle times, presenting a scheduling challenge. Despite this, cost analysis reveals amortization after 1.43 years or 75 projects, highlighting its economic viability and potential for fleet scalability.

Keywords – Construction robotics; Autonomy; Mobile Robotics; Robotics Evaluation Framework (REF)

1 Introduction

The construction industry faces a transformative era of unprecedented demand and significant challenges [1, 2]. With global infrastructure needs surging and urbanization accelerating, the demand for construction work continues to grow. However, a critical labor shortage, driven by a shrinking pool of skilled workers, directly impacts productivity, making it increasingly difficult for the industry to keep pace with rising workloads [3, 4]. This shortage contributes to inefficiencies, as fewer trained professionals can complete projects on time and within budget. As a result, the construction sector continues to lag behind other industries in productivity, highlighting the urgent need for innovative solutions to bridge this gap. Construction projects overrun average cost and time relative to the original budget and schedule at 70 percent and 61 percent, respectively [4]. These delays due to labor shortages and inefficient workflows underscore the need for automation to bridge productivity gaps.

In this context, the market for autonomous construction equipment is emerging as a pivotal force. This market is projected to expand from USD 4.40 billion in 2024 to USD 9.77 billion by 2030 at a compound annual growth rate of 14.2% [5]. Despite its potential, the adoption of automation in construction faces significant hurdles. In Germany, challenges include a rigid labor training structure that mandates three years for operator qualification. A shortage of skilled operators further exacerbates the issue. Procurement practices prioritizing the cheapest bid over innovation pose further challenges. [6]. There is also limited familiarity with robotics or advanced automation, alongside resistance to autonomously driven equipment during operator training. A lack of widespread experience with autonomous systems in construction workflows compounds these issues.

This paper employs the Robotics Evaluation Framework (REF) from Brosque and Fischer [7] to systematically evaluate an autonomous driving dumper, developed by Zöls et al. [8] from the Chair of Materials Handling, Material Flow, Logistics at the Technical University of Munich (TUM) and the dumper manufacturer Wacker Neuson. The REF is a structured methodology designed to evaluate construction robots based on product, organization, process, safety, quality, schedule, and cost metrics.

This paper is structured as follows. Section 2 provides insights into the current development of automated construction equipment. The REF is introduced in section 3, and section 4 applies the REF to the autonomous dumper compared to conventional dumpers to evaluate similar processes and sizes to accurately assess their capabilities. This use case relies on direct testing under lab conditions on the outdoor facilities at TUM. Section 5 presents challenges and opportunities. Finally, section 6 is dedicated to the conclusion and outlook.

2 Literature review

This section explores the landscape of construction robotics, outlining the field's advantages, challenges, and current state of development. Construction robots offer significant potential to revolutionize the construction industry by enhancing efficiency, precision, and safety. These robotic systems, equipped with advanced sensors, actuators, and cognitive algorithms, outperform traditional methods by executing tasks with greater accuracy, yielding higher-quality results with fewer errors [9]. Their ability to undertake repetitive, dangerous, or physically demanding jobs significantly reduces site accidents [10]. By assuming such tasks, robots enable human workers to focus on higher-value activities, fostering safety and efficiency.

While construction robotics presents numerous benefits, the field is still evolving and tackling considerable challenges. Current research primarily emphasizes technological advancements to boost productivity and automate specific construction processes. However, a comprehensive evaluation framework for comparing these technologies, especially against traditional practices, remains absent, highlighting a critical research gap.

Despite the promising advantages, deploying robotics in the construction industry faces challenges due to the dynamic and unstructured nature of construction sites [9–11]. These challenges can be broadly categorized:

- **Safety Challenges:** Ensuring safe robotic operations on crowded construction sites is a critical concern [9]. Multiple activities – often involving workers, materials, and equipment – occur simultaneously, making task execution more complex [10].
- **Process Adaptability Challenges:** Construction processes lack standardization and frequent, unpredictable changes [9, 11]. This dynamic environment demands robotic systems capable of adapting to diverse circumstances and adjusting their actions based on real-time conditions [9, 11].
- **Environmental Challenges:** Uncontrollable weather conditions, such as rain, strong winds, and dust, significantly impact the consistent performance and reliability of robots on construction sites [10].

These factors can degrade sensor accuracy, limit mobility, and impact the overall effectiveness. Achieving full autonomy for construction robots is particularly challenging due to the obstacles posed by unstructured environments and the need for real-time multi-system coordination [11]. Nonetheless, several robots have been successfully deployed to perform specific repetitive tasks that are well-suited for automation.

Construction projects are typically divided into three main tasks: superstructure, substructure, and site preparation [11]. The subsequent sections will explore robotic applications within these categories and related areas.

Table 1 offers an overview of current robotic applications to provide context for the subsequent discussion. These are listed according to their relevance to an autonomous driving dumper. Relevance is judged by process, specific tasks, their on-/off-site usage and whether they are mobile or stationary. The overview also indicates the robot's automation level, based on degrees of freedom and operating conditions. In addition, it shows whether safety, quality, schedule, and cost aspects have been evaluated – aspects detailed further in Section 3.

Table 1. Evaluating relevant construction robotics

Reference	Tasks of robots	Process relevance to dumper	On-site/off-site	Mobile/stationary	Deg. of autonomy	Safety	Quality	Schedule	Cost
[12]	Prefabrication	○	Off	S	◐			X	
[13]	Transport in prefabrication	○	Off	M	◕	X		X	X
[14]	Structural assembly	◔	On	S	◐				
[15]	3D concrete printing	◔	On	S	◐		X		X
[16]	Beam assembly	◔	On	M	◔			X	
[17]	Ceiling board construction	◔	On	M	●	X		X	
[18]	Pile driving	◐	On	M	●		X		
[19]	Waste sorting	◐	Both	M	●		X		
[20]	Excavation	◕	On	M	●		X		
[21]	Material transportation	◕	On	M	●	X	X		
[22]	Material loading	◕	On	M	◐		X	X	
[23]	Material loading and transportation	●	On	M	◐		X		
[8]	Bulk material handling	●	On	M	◐			X	

Drawing from the successful implementation of industrial robot arms in manufacturing, off-site construction presents a viable area for robotics adoption. To address the challenge of non-standardized building components in construction, multi-functional robotic cells are being developed to automate labor-intensive and time-consuming prefabrication processes [12]. Automated Guided Vehicles (AGVs), another mature technology widely utilized in logistics, are also highly relevant. AGVs offer high levels of automation, flexible mobility, and efficient space utilization. This makes them valuable for material handling in stationary prefabrication and module production systems [13].

Transitioning to on-site applications, cable-driven robots have emerged as a versatile solution. Their lightweight design facilitates easy transport and deployment on construction sites [14, 15]. Operated using elevated pulleys, these systems can support full-scale architectural projects. They also adapt to irregular site geometries. For instance, cable-driven robots have been validated for accurately placing granular materials in complex architectural-scale enclosures [14]. Moreover, a cable-driven parallel robot with a concrete extruder demonstrates precise 3D printing capabilities for complex concrete structures. This approach reduces material waste and labor costs while accommodating diverse construction environments [15].

Beyond cable-driven systems, specific robots are designed for repetitive tasks and productivity enhancement on-site. Robotic beam assembly systems automate bolting processes, allowing operators to control robotic transport mechanisms and bolting devices [16, 24]. Ceiling construction robots automate the positioning and installation of ceiling boards [17]. This minimizes the need for human work at elevated positions, improving safety.

In substructure processes, autonomous robots are designed for tasks such as transporting and driving interlocking sheet piles into the soil. This robot ensures precise positioning and interlocking by utilizing a vibratory hammer and its weight, coupled with alignment mechanisms. This enables the construction of continuous stabilization walls [18].

Robotics is also being applied to broader site management tasks. For example, a robotic system equipped with computer vision can autonomously patrol construction sites. It identifies and sorts waste materials and employs optimized gripping strategies for handling diverse waste types and forms [19].

Furthermore, mobile robots are increasingly being developed for earthmoving tasks in site preparation. The hydraulic excavator for an autonomous purpose (HEAP), a walking excavator, demonstrates precise localization, movement tracking, and accurate end-effector control. Its unique wheeled-legged design allows adaptability to uneven terrains, validated in applications like dry stone wall assembly and forestry work [20]. A retrofitted dump truck also showcases autonomous capabilities. It manages steering, acceleration, and braking. Path tracking performance has been evaluated, and an emergency stop feature is integrated to ensure safety [21].

In line with advancements in Artificial Intelligence (AI), autonomous navigation for wheel loaders in short-loading cycles is being explored using reinforcement learning. By decomposing loading tasks, AI agents manage to reverse, reach reversal points, navigate to dump trucks, and control steering, velocity, and bucket positioning [23]. Automated shovel trajectories have been developed and evaluated against manual operation for shoveling. Metrics include full bucket rate, operation time, and fuel consumption [22].

Finally, the autonomous driving dumper, as presented by Zöls et al. [8] with obstacle detection capabilities, exemplifies the potential of collaborative robots in construction environments.

While current robotic applications focus primarily on enhancing productivity, their evaluation often overlooks critical factors such as safety and cost-effectiveness. The REF offers a structured, uniform approach to assess the implementation of construction robots, addressing both practical performance and broader structural considerations [25, 26].

3 Methodology

This analysis focuses on utilizing the REF, a methodical tool used for uniform evaluations of the integration of robotics and autonomous systems into construction sites [7]. The REF was selected for this study due to its structured approach to assessing the integration of robotics into construction projects. The REF balances feasibility, performance, and risk considerations, offering a comprehensive evaluation addressing technical and operational factors critical to successful deployment. The REF consists of two key stages. The first stage evaluates the feasibility of deploying a robot on a project [7, 27]. This is done by analyzing three independent variables – product, organization, and process – referred to as the POP analysis:

1. **Product:** Evaluates robot features for the work environment.
2. **Organization:** Assesses worker and organizational requirements.
3. **Process:** Covers operational changes, quality assurance, and documentation.

After determining feasibility through the POP analysis, the REF then evaluates the overall performance and impact of robotic implementation compared to manual construction through the SQSC analysis, which focuses on safety, quality, schedule, and cost. This offers a comparison between robotic implementation and manual deployment [7, 27]:

4. **Safety**: Focuses on quantifying the impact accidents, ergonomic strain, and hazards.

5. **Quality**: Evaluates the accuracy of robotic construction work.
6. **Schedule**: Assesses task completion time with robots vs. traditional construction.
7. **Cost**: Compares initial investment to long-term returns.

4 Use Case

4.1 Overview

The REF methodology is being implemented on the autonomous driving dumper, developed by the Chair of Materials Handling, Material Flow, Logistics at the Technical University of Munich (TUM) together with the industry partner Wacker Neuson (see Figure 1). It is compared with its conventional counterpart, Wacker Neuson DT10e Dumper and is evaluated in terms of feasibility and advantages for the use on-site.

Figure 1. Autonomous dumper project, developed by TUM and Wacker Neuson

4.2 POP analysis

The first step is to perform an initial feasibility check for the robot, in this case, the autonomous dumper, using the POP analysis.

4.2.1 Product analysis

To perform product analysis, thorough information was gathered through dispatched observations based on pictures, videos, and interviews with researchers, industry partners, and instructors. The objective of the autonomous dumper is to transport bulk materials on construction sites. The dumper has a high degree of mobility, making it capable of remote control operation or even following autonomously. In the future, this equipment might interact with other dumpers or equipment at the site. The dumper has a steering interface, a remote control via WLAN, and sensors such as IMUs for the position of the bucket, the loading unit, and the main vehicle, GNSS for the global position, cameras for object detection, and ultrasonic sensors for safety reasons. Sensor data is processed locally by the autonomous dumper. Weighing 680 kg and featuring a ground clearance of 80 mm, the autonomous dumper can operate in harsh conditions. However, challenges may arise during heavy rain when certain sensors struggle to detect objects. The dumper is not commercially available, as it is part of a research project at the Chair of Materials Handling, Material Flow, Logistics at the TUM. Its potential applications extend to any construction site requiring the transportation of bulk materials in confined spaces.

4.2.2 Organization analysis

Introducing the autonomous dumper into the construction process offers some organizational advantages. In Germany, operators must undergo three years of training before operating heavy equipment, making the existing manual labor shortage more noticeable. Using the autonomous dumper requires less training, and the operator can simultaneously work on multiple pieces of equipment, allowing for a more efficient work outcome. Instead of a conventional dumper, one can use one or multiple autonomous dumpers and improve flexibility on the construction site. However, there is no experience with robots or higher levels of automation, and there is little acceptance of electric or automated equipment at the training grounds.

4.2.3 Process analysis

The processes were analyzed using the videos provided for the autonomous dumper, the results of Zöls et al. [8], and expert interviews at the Bayerische Bauakademie. There are some process changes when switching from the conventional to the autonomous dumper. The communication shifts from verbal to digital. While transporting bulk materials is not typically considered a value-adding task, basic quality control measures — such as ensuring load stability and minimizing spillage — are still relevant. In this use case, manual and autonomous dumpers maintain similar standards in these areas, leading to no significant difference in quality outcomes. There are also no progress reports on a process level, except for a construction load, which documents whether an area is cleared. The detailed workflows of manual and robotic construction are depicted in Figure 2.

The process for the conventional dumper begins with the operator starting the vehicle and getting on the equipment. The operator starts with the loading process, which takes 51s. Then, the operator maneuvers the load to its destination for 51s and unloads it within 11s. To end the process, the operator drives to the starting point for

23s while being empty.

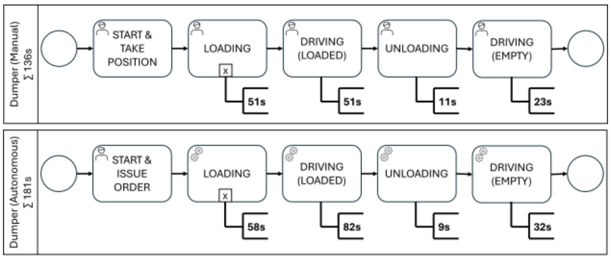

Figure 2. Comparison of the conventional and autonomous dumper

The workflow of robotic construction is slightly different. The process begins with the operator providing the autonomous dumper with its task. After this, no interaction with the operator is required, and the operator can focus on value-adding tasks. The process for the autonomous dumper follows the process of the conventional dumper. The loading takes about 58s, the driving with the load 82s, the unloading 9s, and the driving with no load 32s.

Since the conventional and autonomous dumper can perform similar tasks, the initial feasibility check for the process is positive. All three independent variables check positive for the initial feasibility. This allows for further investigation of this project according to the dependent variables to assess the impacts of deploying the robot.

4.3 SQSC analysis

The dependent variables are now evaluated following the SQSC analysis and the initial feasibility check. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was selected for this evaluation because it ranks alternatives based on multiple criteria. It effectively balances safety, quality, schedule, and cost factors. This allows for weighted prioritization — such as emphasizing safety over minor schedule delays. This approach ensures a comprehensive assessment of the autonomous dumper’s performance relative to manual operations [28]. Safety, given its paramount importance, has a TOPSIS weight of 0.5. Quality, with a TOPSIS weight of 0.1 is less critical since the transportation of bulk materials does not have strict quality standards that either equipment could compromise. The schedule is assigned a weight of 0.2, reflecting the importance of clearing areas within a reasonable timeframe. Costs are also weighted at 0.2, highlighting the need to offer the robot solution competitively.

4.3.1 Safety Analysis

In manual operations, safety depends on several factors. The operator's level of experience plays a crucial role. Additionally, safety is influenced by how well workers adhere to safety rules, such as avoiding movement in blind spots. Manual operation exposes the operator to constant vibrations, impacting health and performance over time. The age of the dumper also impacts safety, as does the type of dumper, particularly in terms of its ergonomics connected to comfort variables. In robotic operations, safety is determined by different criteria. The effectiveness of sensors and software is paramount. The type of human interaction required also affects safety, as does the level of collaboration between humans and robots. The autonomous dumper demonstrated better safety outcomes in terms of ergonomics compared to manual operation, reducing repetitive tasks for operators by 10%. This lowers the risk of strain-related injuries due to vibrations since the operator does not have to stand on the dumper.

4.3.2 Quality Analysis

In manual operations, the quality depends on the operator's experience for accuracy and repeatability, and it is comparable to that of robots. The operator's experience influences the rework needed, but it tends to be slightly better than that of robots. Material waste is excluded since the use case involves transporting bulk material. In robotic operations, the quality depends on the effectiveness of sensors and software for accuracy and repeatability, and it is comparable to that of a conventional dumper. The sensors and software influence the needed rework. Material waste is also excluded from consideration since the use case involves transporting bulk material.

4.3.3 Schedule Analysis

The schedule was evaluated according to Figure 2. The cycle times for the conventional and the autonomous dumper of bulk material are calculated as the sum of the different subprocess times of loading, driving (loaded), unloading, and driving (empty). The overall cycle time of the conventional dumper accumulates to 136s. The cycle time of the autonomous amounts to 181s which is about 20% higher.

4.3.4 Cost Analysis

An autonomous dumper's purchase price is higher than a conventional dumper's, increasing initial capital expenditure (+52.42k euros). However, conventional dumpers lack sensors, limiting automation, while autonomous dumpers are equipped with advanced sensors that enhance efficiency and safety (+5k euros). Conventional dumpers demand more human labor (+22 hours or +1k euros using 44,50 euros/hour), often requiring both an operator and a helper. In contrast, one operator can oversee multiple autonomous dumpers, optimizing labor costs. In total, the costs for the autonomous dumpers are only 2 % higher (+4k euros p.a.). Autonomous dumpers are cost-competitive for smaller projects with high labor needs, as they handle smaller bulk loads with minimal operator support, making them ideal for confined sites. By enabling operators to focus on value-adding tasks, these dumpers boost productivity. They could also function in collaborative fleets, improving efficiency and reducing project duration and costs [29]. According to the REF framework, autonomous dumpers are viable and cost-effective for small to medium-scale projects, with a payback period of approximately 1.43 years or 75 projects for a full 4-year utilization.

4.3.5 Sensitivity Analysis

In the assessed case, the autonomous dumper outperforms the conventional dumper in the REF. A sensitivity analysis was conducted to further evaluate the performance of the conventional and autonomous dumper. The sensitivity analysis explored variations in cost and cycle time, with deviations of ±25%, ±50%, and ±75%. Results showed that while increased cycle times negatively impacted schedule performance, the autonomous dumper consistently outperformed manual operations in safety and cost metrics. The dumper maintained economic viability even under conservative cost assumptions, with amortization still achievable within 1.6 years. These findings confirm the robustness of the autonomous solution across varying operational scenarios.

5 Challenges and Opportunities

Adopting autonomous construction equipment like the Wacker Neuson DT10e Dumper offers opportunities and challenges. Safety is paramount, requiring reliable systems and technologies like SLAM-based dynamic mapping to ensure seamless integration with workers and equipment, which must be tested across varied conditions to build trust. Limited acceptance of autonomy, particularly in training environments, and the need for effective collaboration with traditional equipment are notable hurdles. The initial dumper tests have demonstrated key safety enhancements in autonomous operation. Unlike conventional dumpers, the autonomous DT10e eliminates operator exposure to vibrations, significantly improving ergonomics. Additionally, the dumper has advanced human-recognition capabilities, allowing it to detect nearby workers and either follow or stop accordingly. These safety features enhance on-site interaction between autonomous and manual operations, reducing the risk of accidents and improving overall workflow efficiency. Scalability also demands advanced systems to manage interconnected fleets. Advanced systems might involve a combination of centralized fleet management software, real-time data-sharing platforms, and robust communication networks.

Despite these challenges, the potential benefits are substantial. The autonomous dumper’s compact size and ability to handle lighter loads make it ideal for smaller projects, automating transport tasks so workers can focus on value-adding activities and boosting productivity. Scalable fleets of dumpers could reduce costs and downtime, even competing with wheel loaders. Dynamic mapping enhances collaboration, enabling integration with connected fleets or complementary products like vibratory plates. Contractors can improve efficiency by outsourcing non-value-adding tasks, while manufacturers like Wacker Neuson have the opportunity to expand their market by offering interconnected fleet solutions. The REF evaluation underscores the dumper’s potential to address labor shortages, improve efficiency, and drive construction industry innovation.

6 Conclusion and Outlook

The REF evaluation of the autonomous Wacker Neuson DT10e Dumper demonstrates its potential to enhance construction workflows. While quality remains comparable to conventional dumpers, the autonomous system experiences 20% longer cycle times, presenting a scheduling challenge. Despite this, cost analysis reveals amortization after 1.43 years or 75 projects, highlighting its economic viability and potential for fleet scalability. Currently, the dumper’s autonomy is limited to driving. Extending its capabilities to include automated loading and unloading would enable fully autonomous bulk material transport, reducing the need for human intervention and increasing operational efficiency. In doing so, it can complement larger equipment, allowing operators to focus on value-adding tasks. In the future, fleets of dumpers could improve efficiency, generate dynamic site maps, and adapt to smaller projects or confined spaces [29]. Future advancements in autonomous dumpers could be driven by integrating AI for task coordination, path planning, enhanced sensor systems for improved real-time obstacle detection, and robust communication networks to facilitate seamless data exchange between machines in a fleet. These technologies enable more complex, coordinated operations, improving overall site efficiency and safety. Future REF studies could explore the scalability of autonomous dumpers and their performance in complex earthmoving tasks, particularly by comparing autonomous fleets to larger traditional equipment.

This paper underscores the value of the REF as a systematic framework for evaluating construction robotics, supporting informed decision-making, and promoting the integration of innovative technologies. While challenges such as acceptance and scalability remain, the findings underscore the promise of autonomous dumpers to boost productivity and drive innovation. Autonomous construction robotics, such as the Wacker Neuson DT10e Dumper, hold significant potential to address key industry challenges, including labor shortages, low productivity, and the growing demand for innovation and automation in construction workflows. Advancements in technology and broader adoption of REF will be crucial for realizing the full potential of construction robotics.

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