Proposal of a Benchmark Indicator for Automated Construction Technology

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Abstract -

In recent years, the construction industry has urgently needed to address labor shortages caused by an aging workforce and population decline, drawing increasing attention to automated construction technologies. In this paper, focusing on earthworks, we propose a benchmark indicator composed of two levels: an 'automated construction level', which expresses the degree of technical sophistication following the example of autonomous driving levels in automobiles, and a 'social implementation level', which represents the degree of dissemination of technology through stages from research and development to market adoption. By introducing this indicator, we aim to assess both the automation level of construction machinery operations and the extent of their widespread use.

Keywords -

Autonomous Construction; Benchmark; Earthworks

1 Introduction

The construction sector is confronting a confluence of challenges: demographic shifts have led to a dwindling, aging workforce, tight labor markets push up costs, and the complexity and scale of projects continue to increase [1]. As traditional workflows prove insufficient to meet rising demands for quality, speed, and cost-effectiveness, automation emerges as a critical enabler for enhancing productivity, improving safety, and ensuring operational continuity. Prominent initiatives, such as Japan's i-Construction2.0 [2], aim to boost productivity by integrating advanced digital technologies, automated equipment, and streamlined data exchange mechanisms, aspiring to a 30% reduction in workforce demands by 2040.

Yet merely deploying automated machines is not enough. The industry needs robust frameworks to evaluate the maturity and broader impacts of emerging technologies. An Automated Construction Level (ACL), inspired by autonomous driving classifications defined by the Society of Automotive Engineers, has been proposed to map out the progression from manual operations (Level 0) to fully autonomous site management (Level 5) [3]. However, focusing solely on technical sophistication neglects the equally important dimension of societal acceptance and diffusion. For instance, even a highly advanced technology might remain confined to experimental testbeds if it fails to address market needs, instill user trust, or integrate smoothly with existing practices.

To address this gap, we introduce a benchmark that integrates the ACL with a Social Implementation Level (SIL), inspired by Moore's Chasm Theory [4], Rogers' Diffusion of Innovations [5], and complementary concepts such as Adoption Readiness Levels and Technology Readiness Levels [6]. By defining a two-dimensional matrix, we can situate technologies in terms of both their technical automation maturity and their stage in the social adoption lifecycle. This dual perspective informs developers about the importance of standardizing core planning processes before full automation, encourages investors to calibrate risk based on market penetration rates, assists policymakers in identifying where strategic support might be most effective, and enables end-users to choose tools aligned with their operational readiness.

ARL (Adoption Readiness Level), in particular, focuses on the commercial adoption process and social risks that cannot be fully captured by technological maturity alone. While this broad scope offers a multifaceted perspective, it can make the stage of technology adoption less intuitive to grasp. Meanwhile, evaluating automation in construction requires a comprehensive approach that considers not only the automation level of the machinery itself but also the automation of construction management processes. Although TRL (Technology Readiness Level) is widely used as a general framework for assessing technological maturity, it remains challenging to comprehensively evaluate automation under the diverse conditions unique to construction sites without adopting the SAE-based concepts employed in automotive autonomous driving—namely, DDT (Dynamic Driving Task) and ODD (Operational Design Domain). By aligning our new framework with insights from ARL and TRL, we aim to capture the interplay between technical progression and societal uptake more holistically, while remaining sufficiently tailored to the realities of the construction industry.

In the following sections, we first elaborate on the concept of Automated Construction Levels (ACL), then propose a parallel Social Implementation Level (SIL), and finally integrate both to form a two-dimensional benchmark. We illustrate this approach with references to current examples of construction automation—such as partially and fully automated machines—and discuss how the combined ACL–SIL matrix can guide various stakeholders in decision-making and policy formulation.

2 Automated Construction Level: Beyond Machine Autonomy to Systemic Intelligence

The ACL framework to date has ranged from:

- **Level 0:** Manual operation with no automation.
- **Level 1:** Operator assistance (e.g., machine guidance) that augments human control while leaving most decision-making to the operator.
- **Level 2:** Partial automation of specific machine functions (e.g., automated blade control), reducing the cognitive load and skill barrier.
- **Level 2.9:** Full automation of a single machine's essential tasks, effectively removing the need for direct operator input in core operations.
- **Level 3:** Coordinated automation across multiple machines on a single site, yet still reliant on site-specific human planning.
- **Level 4:** Automated planning and task allocation, leveraging site data and design schematics to direct multiple machines autonomously within defined operational parameters.
- **Level 5:** Full autonomy across machines and tasks, unrestricted by predefined Operational Design Domains (ODD).

We propose an additional stage: **Level 3.5**, focusing on the generalization and systematization of the construction planning process—known in Japanese practice as "dandori." While Level 3 demonstrates that automation can handle a particular site's complexity, scaling this capability to diverse conditions demands codifying planning logic into a machine-readable, standardized framework. By achieving Level 3.5, developers set the stage for more readily attainable Level 4 and 5 solutions.

Examples from the industry underscore the necessity of this intermediate level. Current site-level automation cases, such as automated dam and tunnel construction using coordinated fleets of machinery [7], rely heavily on expert planners and site managers. Without codifying these human planning heuristics, scaling up remains prohibitively expensive and complex. Level 3.5 thus represents a strategic stepping-stone: it encourages a focus on knowledge representation, standardized planning protocols, and interoperable data models.

3 Social Implementation Level: Aligning Market Penetration with Trust and Adoption

Technological capability alone does not guarantee acceptance. Innovations must navigate the chasm between early enthusiasts and the mass market. Drawing on Moore's Chasm Theory and diffusion models, we categorize social implementation into:

- **Level 1:** Laboratory-scale R&D, prototypes, and pilot projects with negligible market presence.
- **Level 2:** Limited field trials and early demonstrations, potentially with small-scale commercial pilots.
- **Level 3:** Initial commercialization with constrained market penetration, adopted by specialized or niche segments.
- **Level 4:** Approaching the "chasm", technology gains footholds in multiple segments, nearing the early market's 16% threshold. Customer testimonials and early references start to build trust.
- **Level 5:** Stable adoption exceeding approximately 20% market share, suggesting a shift from novelty-driven acceptance to widespread trust and integration into industry norms.

The precise definition of market share depends on selecting an appropriate reference population. Construction markets are heterogeneous: a technology suitable for large-scale earthworks in infrastructure projects might not translate directly to residential or specialty construction. Thus, determining the relevant "market universe" is essential. Efforts to standardize reporting—potentially through industry associations or regulatory bodies—could help normalize these metrics.

4 Integrating the Two Axes: A Two-Dimensional Benchmark

By plotting ACL on one axis and SIL on the other, we create a two-dimensional matrix (Figure 1) that situates technologies within a nuanced landscape. For instance:

- **Teleoperation (ACL 0, SIL 3):** Remote controlled machines have been proven in disaster recovery since the 1990s [8]. Although technologically simple (human-operated), their wide acceptance in niche

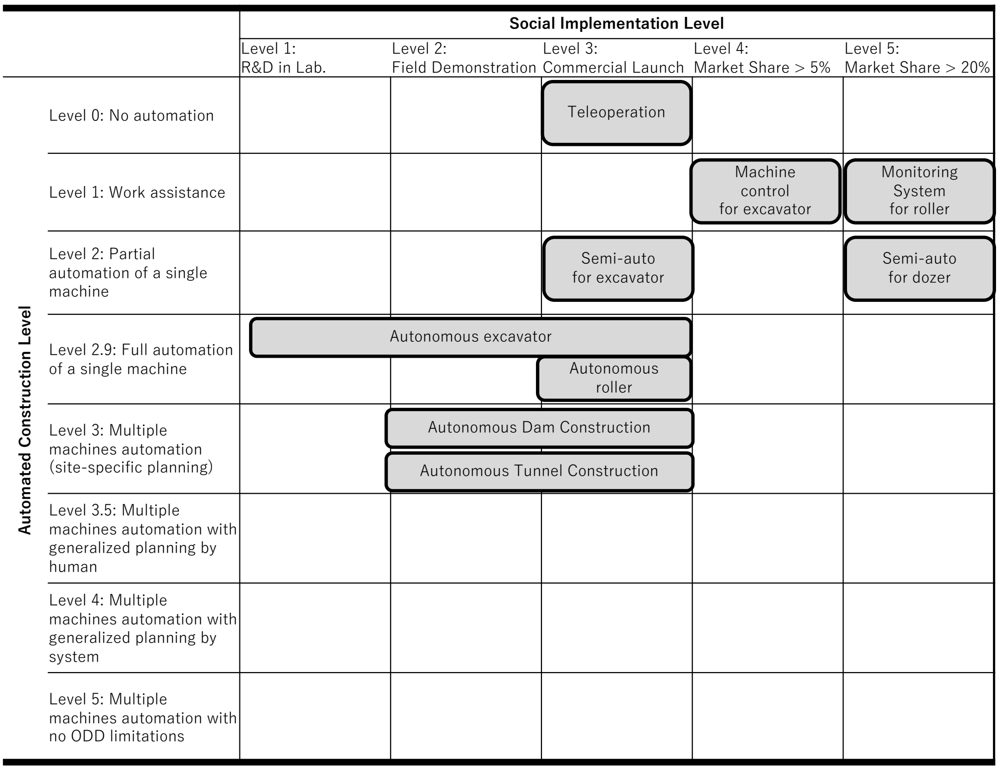

Figure 1. Evaluation of Automated Construction Technology Using Benchmark Indicators

scenarios places them around Social Implementation Level 3.

- **Machine Control System (ACL 1, SIL 4-5):** . In Japan, it is called machine guidance. Excavator machine control systems using GNSS, laser-based sensors, and 3D design data are widely available. Multiple manufacturers offer them and, in some regions, more than half of excavators can incorporate guidance features, pushing them into SIL 4 or 5.
- **Semi-auto system (ACL 2, Various SIL):** In Japan, it is called machine control. Automated blade control for bulldozers or partial autonomy in hydraulic excavators can boast significant market penetration, potentially reaching SIL 5 for certain machine categories [9].
- **Fully autonomous machine (ACL2.9, SIL 1-3):** Most fully autonomous machines remain trapped at R&D or prototype levels (SIL 1-2) [10, 11, 12, 13]. However, some autonomous excavator and roller have already been launched [14, 15].
- **Site-Level Automation (ACL 3, SIL 2-3):** Projects such as automated dam and tunnel construction [7] exemplify site-wide automation. However, these remain bespoke, heavily engineered solutions, with minimal standardization and limited replication across diverse projects.

Crucially, we find no examples at ACL 3.5, 4, or 5, nor do we see technologies in widespread, stable mainstream use at a corresponding SIL for these higher ACLs. This observation reveals a strategic opportunity: bridging the technical and social dimensions is not simply about incremental improvement, but about systemic change, collaborative data standards, and knowledge exchange.

5 Discussion and Future Directions

Our benchmark reveals that while some technologies, such as machine guidance, are well integrated and widely trusted, others, such as fully autonomous excavators or site-level systems, remain at an early stage. For researchers and developers, ACL 3.5 stands out as a priority: codifying planning processes to reduce site-specific engineering costs. Investors, meanwhile, can better calibrate risk by noting whether a technology aligns with established mainstream practices (SIL 5) or remains experimental (SIL 1–2). Since there are still few real-world cases in ACL 3 or higher, further development of these technologies should be accompanied by large-scale empirical studies and rigorous statistical analyzes to thoroughly validate and refine the proposed benchmark.

Policymakers can use these metrics to allocate resources and encourage standardization. Supporting common data protocols, testbeds, and training could streamline the transition from isolated successes to broad adoption. Practitioners benefit by selecting tools that match their operational readiness and understanding whether a particular solution is proven or still exploratory.

Future refinements may involve adding sub-levels, incorporating sustainability metrics, or considering regional market nuances. Aligning this benchmark with efforts in related industries—such as automotive or mining—could further enhance its clarity and relevance. As the construction automation ecosystem evolves, continuous feedback will help refine both ACL and SIL scales, ensuring they remain practical and reflective of real-world conditions.

6 Conclusion

This paper introduced a benchmark framework that unites technical maturity (Automated Construction Level) with societal diffusion (Social Implementation Level) to provide a holistic perspective on automated construction technologies. By incorporating a novel ACL 3.5 stage that emphasizes the formalization of planning logic, and linking market penetration milestones to known thresholds of consumer acceptance, the benchmark reveals strategic development pathways and potential gaps.

In practice, this framework offers value to multiple stakeholders: researchers gain clearer R&D targets, developers appreciate the importance of systematic planning processes, investors gauge market readiness more accurately, policymakers identify priority support areas, and practitioners discern which technologies fit their current needs. Although still in a formative stage, our benchmark invites further input, adaptation, and validation. By continually refining these metrics, the construction industry can move toward more transparent, data-driven decision-making and accelerate the meaningful adoption of automation on construction sites worldwide.

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