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COMMENTS

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Rethinking engineering management for human–robot collaboration from technological and social perspectives

Abstract The rapid evolution of robotic and intelligent technologies is propelling the construction industry toward human–robot collaboration. Consequently, robots have transcended their role as mere instruments of labor to acquire the attributes of laborers, forming a human–robot hybrid workforce that jointly undertakes productive activities. The emergence of this new labor paradigm is poised to trigger unprecedented transformations in project division of labor, organizational structure, technological coordination, management models, and governance mechanisms. However, existing research lacks a systematic understanding of this transformation and its potential cascading effects. Therefore, this paper adopts a sociotechnical systems framework to analyze human–robot collaboration, examining the technological evolution of construction robots from tools to partners and the corresponding shifts in collaboration patterns. Furthermore, drawing on the Leavitt model, human–robot collaboration is conceptualized as a coupled configuration of "people–technology–task–structure." This perspective enables an integrated analysis of how the technical and social attributes of human–robot collaboration reshape both the technical logic and managerial paradigms of engineering management. Finally, this study identifies ten key research topics reflecting the emerging characteristics of human–robot collaboration in the construction industry, aiming to illuminate future frontiers of this transformation in engineering management.

Keywords human–robot collaboration, engineering management, sociotechnical system

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1 Introduction

As an entrenched traditional sector, the construction industry grapples with systemic challenges including labor scarcity, resource-intensive operational paradigms, and underdeveloped digital-industrial integration, and is now confronting a dual deficit of workforce availability and specialized skills. Disruptive progress in core enabling technologies, artificial intelligence (AI), materials science, and automation—is redefining the robotics industry's developmental trajectory. In the construction industry, robots show increasing promise for tasks that are highly repetitive, physically demanding, or hazardous, offering a potential path to mitigate workforce constraints and improve efficiency (Chen and Adel, 2025). McKinsey & Company (2017) estimates that the construction industry has an automation potential of up to 47%. A global survey by Asea Brown Boveri (ABB) shows that 81% of construction companies plan to adopt or expand robotic systems by 2030 (ABB, 2021). In a more recent projection, McKinsey & Company (2023) projects that robotics and automation will account for 25% of capital spending across industrial sectors over the next five years. Leading global robotics companies such as ABB, FANUC, and Boston Dynamics have actively entered the construction market, developing specialized robots for measurement, masonry, material handling, and spraying tasks (Paraschо, 2023). Construction robots are gradually being integrated into various site operations, demonstrating strong potential to emerge as a new form of intelligent labor.

The fundamental impetus behind robotics development was to emancipate humans from mechanistic and procedural labor. The convergence of diverse digital technologies has enabled robots to be equipped with capabilities of perception, cognition, decision-making and execution, which are functionally convergent with human capacities (Kirtay et al., 2023). An editorial in Nature Machine Intelligence named Robot planning with LLMs (2025) notes that robots not only demonstrate greater efficiency and adaptability in standardized tasks, but are also capable of interpreting ambiguous instructions, planning long-horizon actions, and flexibly adjusting their behavior in unstructured environments based on visual and force feedback. At the same time, they compensate for inherent human limitations in physical endurance, sustained operation, and attention control, further expanding their range of applicable scenarios (Zhang et al., 2023). Amidst rapid technological iteration, robots are evolving from tools and equipment into quasi-human labor entities. This represents a paradigm shift transcending their traditional status as instruments of labor toward acquiring laborer attributes, thereby co-constituting a human-robot dyad within productive engagement.

When robots function as co-equal agents of labor execution, engineering projects undergo unprecedented transformations in their division of labor, organizational forms, technological coordination, management models, and governance mechanisms. This study adopts both technological and social perspectives to systematically examine how robotic technologies are embedded in the construction industry and reshape engineering management practices. It focuses on deconstructing the evolutionary trajectory of robotic capabilities and the resulting transformations in human–robot interaction, social relations, and organizational forms. The aim is to uncover the underlying logic driving the transition of human–robot collaboration and to provide insights for advancing theory and practice in engineering management.

2 The technical and social attributes of human–robot collaboration in engineering management

The application of human–robot collaboration in engineering management goes far beyond mere tool substitution or functional enhancement; it embodies a complex interplay between technical elements and social structures. To unpack this intrinsic complexity, this paper adopts the sociotechnical systems theory as its core analytical framework. This theory has been widely applied to interpret the interaction between technology and social organization, emphasizing that high-performing systems arise from the co-optimization of its technical and social subsystems. The technical subsystem of human–robot collaboration encompasses robotic capabilities in perception, decision-making, and execution—integrating both hardware and algorithmic dimensions. The social subsystem, in contrast, involves patterns of collaboration, role allocation, trust building, and organizational culture among participants. These two subsystems are deeply interwoven and mutually shaping, collectively determining the overall effectiveness of human–robot collaborative systems. Accordingly, human–robot collaboration can be regarded as an integrated system that possesses both profound technical and social attributes. Its technological dimension concerns how collaboration is achieved—covering issues of capability, interaction, and efficiency—which forms the foundation of collaboration. Its social dimension focuses on what impacts collaboration brings and how these impacts are governed, involving aspects such as work practices, ethics, and trust, which ultimately determine whether collaboration can be accepted and sustained.

2.1 Technical attributes of human–robot collaboration

The technical attributes of human–robot collaboration refer to the capabilities that construction robots have progressively acquired through the rapid advancement of modern information technologies. These robots now demonstrate human-like abilities in perception, cognition, decision-making, and execution, and their capability systems have become increasingly well developed (Ma et al., 2022). Specifically, perception relies on technologies such as multimodal sensors and point cloud recognition to acquire environmental information. Cognition relies on the application of knowledge graphs and large language models, which support semantic interpretation and logical inference. Decision-making combines reinforcement learning with optimization algorithms to enable robots to determine action pathways and formulate strategies. Execution is realized through model predictive control and digital twin technologies, which ensure accurate task performance and facilitate seamless collaboration with human workers.

However, the capabilities of construction robots are not fully established at once; rather, they evolve progressively through a gradual developmental process, as illustrated in Fig. 1. Drawing on stage-based classifications from industrial robotics and autonomous systems (Gasparetto and Scalera, 2019; Melenbrink et al., 2020), recent studies on capability maturity assessment for construction robots have identified five representative stages of development (Yao et al., 2025).

(1) Initial: The robot operates as a purely mechanical or passive executor, limited to repetitive and rule-based tasks, with no intelligence. Its function remains equivalent to that of traditional tools.

(2) Starting: The robot demonstrates basic perception and execution abilities, such as path recognition and assembly operations. However, it lacks the coordination needed for complex and multitask construction.

(3) Development: The robot begins to integrate perception, execution, and basic decision-making in a preliminary manner. It can autonomously complete standardized subtasks and functions as a practical extension of human labor.

(4) Advanced: The robot exhibits maturity across perception, cognition, decision-making, and execution. It is capable of handling unstructured tasks and synchronizing with human workers in information flow and task

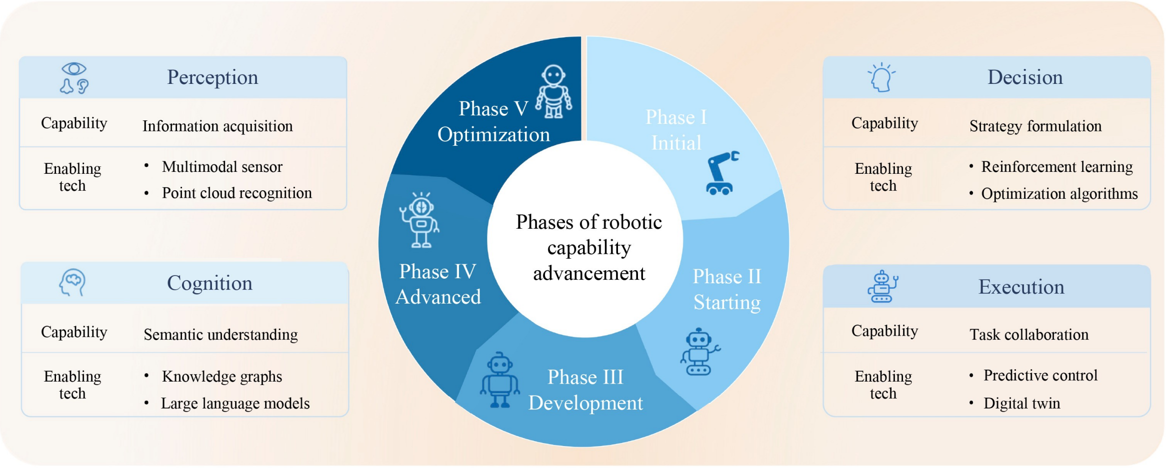

Fig. 1 Capability structure and development stages of construction robots.

rhythm. In this stage, it operates as an autonomous collaborator.

(5) Optimization: The robot acquires the ability to adapt through learning and to generalize across different scenarios. It becomes embedded in organizational workflows, takes part in task allocation and localized decisions, and moves closer to fulfilling the role of a technical agent comparable to a human.

In engineering practice, construction robots are increasingly exhibiting "human-like" capability characteristics. Multimodal perception and semantic modeling enable robots to achieve human-like situational awareness in complex environments (Wang et al., 2022). Kinematic optimization and augmented reality technologies enhance their operational precision and collaborative performance under constrained conditions (Xiang et al., 2021). With advances in algorithmic optimization, robots can now organize assembly sequences and allocate resources more efficiently (Funk et al., 2022). The integration of reinforcement learning and imitation learning allows them to adopt adaptive strategies for dynamic tasks such as defect detection (Zeng et al., 2020). The incorporation of large language models further endows robots with human-like reasoning, combining semantic understanding with visual perception to generate context-aware task plans (Wang et al., 2025a). Moreover, digital twin technology embeds robots within construction workflows, enabling iterative calibration, real-time coordination, and more proactive collaborative execution (Wang et al., 2021). However, most existing studies remain focused on performance enhancement and task-level optimization, while insufficient attention has been given to collaboration as a systemic capability. The role of robots as collaborators, rather than as simple tools, has yet to be thoroughly examined.

2.2 Social attributes of human–robot collaboration

Against the backdrop of technological humanization, the attributes of human–robot collaboration are reflected not only in functional execution but also in social interaction and organizational restructuring. The social attributes of human–robot collaboration focus on its impact on "soft" dimensions such as individuals, organizations, social relationships, and ethical norms. To complement the characterization of the social attributes of human–robot collaboration, it is necessary within the overarching framework of sociotechnical systems to introduce theoretical approaches that refine the understanding of its social dimension. The theory of technological anthropology explains how technology attains agency and participates in role configuration, while human–machine sociology interprets the formation of relationships, norms, and social order within human–machine interactions. Together, these two perspectives provide complementary explanations of the social dynamics underlying human–robot relations. Technological anthropology was first introduced by the German scholar Hans Sachsse, who challenged the traditional view of technology as a neutral tool and instead regarded it as an extension of the human body (Wang, 2021). French scholar Pierre Lemonnier further emphasized that technology exhibits agency and social interactivity in the processes of use and transmission, arguing that technology itself possesses both the capacity to act and inherent social attributes (Lemonnier, 1986). Wang et al. (2023) argued that the functional complementarity between humans and machines fosters a shift in human–machine relations from machine "assistance and subordination" to human–machine "collaboration and equality," where both are recognized as equal social agents. Human–machine sociology further emphasizes that humans and machines together constitute an interdependent hybrid social system, in which collective outcomes emerge from their interactions rather than from either side alone (Tsvetkova et al., 2024). This systemic understanding is reflected in the evolving role of construction robots, which are increasingly embedded in organizational contexts as intelligent agents with autonomous decision-making capabilities. Human–robot collaboration is thus shifting from linear task coordination toward structural cooperation, driving systemic transformations in both collaboration patterns and organizational mechanisms.

2.3 Human–robot collaboration model

At present, there is no universally accepted definition of human–robot collaboration. Existing studies mostly delineate its boundaries in terms of temporal and spatial relationships. When humans and robots work together in the same place and at the same time, engaging in direct interaction during operation or decision-making, such activities can be regarded as collaboration (Liu et al., 2025). In this paper, construction human–robot collaboration is defined as the process in which workers and construction robots jointly accomplish construction tasks within a shared or adjacent workspace that allows mutual influence, aiming toward a common project goal. The essence of collaboration does not lie in whether a robot performs a specific task independently, but in whether humans and robots are interdependent in execution or decision-making—whether the perception or action of one party can be sensed, interpreted, and subsequently used by the other to adjust its behavior. As robotic autonomy and capability continue to advance, construction robots have evolved from auxiliary tools to autonomous agents capable of performing standardized operations and engaging in task-sharing with human workers through understanding and decision-making. Accordingly, based on the degree of robotic autonomy and the depth of human–robot interaction (Liang et al., 2021; Rodrigues et al., 2023), this paper identifies five representative modes of construction human–robot collaboration, as illustrated in Fig. 2. Taking purely manual operation as the baseline, these modes follow an evolutionary trajectory from machine assistance to human–robot operational collaboration, cognitive collaboration, and ultimately, collaborative clusters of multiple robots.

Model 0: Fully manual execution

Workers are solely responsible for the entire task process, relying entirely on human judgment and experience. While this approach offers high adaptability to complex or dynamic environments, its efficiency is inconsistent, representing the most traditional form of operation.

Model 1: Human–robot assistance

Robots are integrated into the workflow as mechanical devices, operating under human supervision and providing technical support. Humans retain full control over task execution, while robots handle repetitive, heavy physical work or labor-intensive tasks.

Model 2: Human–robot execution collaboration

Humans and robots jointly participate in both task decomposition and execution, with a focus on process-level coordination. Humans are responsible for complex reasoning and adaptive decisions, whereas robots perform standardized operations. This mode enables synchronization in both task rhythm and information flow.

Model 3: Human–robot cognitive collaboration

Humans and robots establish mutual information exchange and feedback mechanisms to support joint decision-making and real-time task adjustments. Robots not only execute commands but also respond autonomously

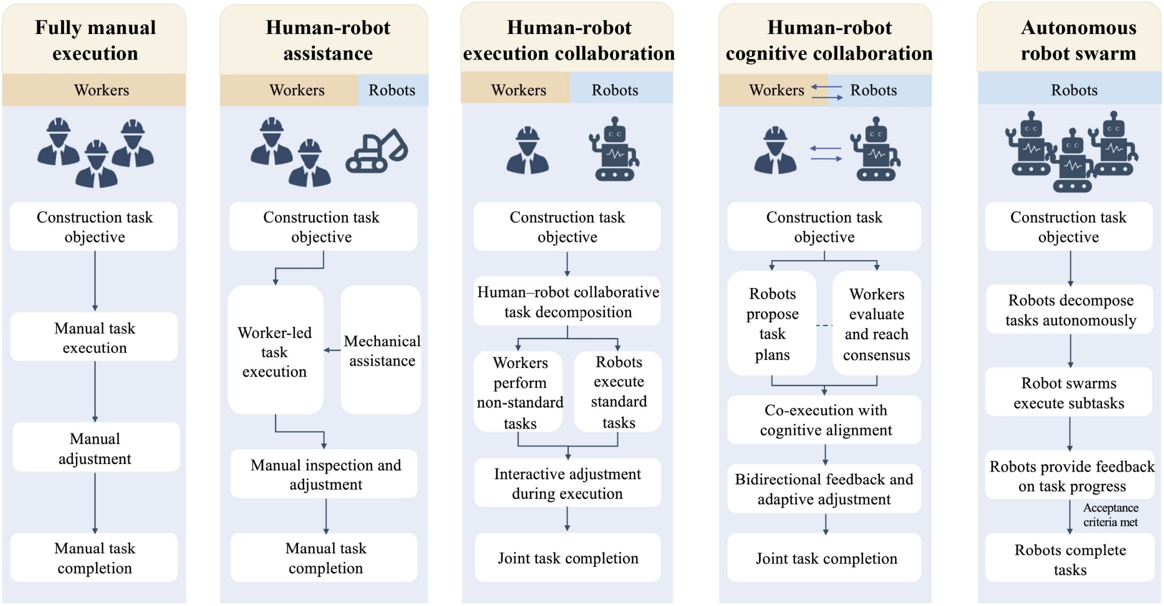

Fig. 2 Five models of human–robot collaboration in construction.

to human input. This reflects a more interactive and egalitarian mode of collaboration.

Model 4: Autonomous robot swarm

Robots independently decompose and execute tasks, while humans assume roles in scheduling, monitoring, and exception management. Multi-robot systems achieve decentralized coordination, and human involvement shifts from direct task execution to higher-level system supervision.

3 New characteristics and emerging directions in engineering management shaped by human–robot collaboration

As a complex sociotechnical system, human–robot collaboration embodies both technical and social attributes. These attributes do not exist in isolation but coevolve through dynamic interaction, driving a profound shift in the engineering management paradigm. To systematically analyze the underlying mechanisms of this transformation, this study adopts the Leavitt sociotechnical model as its analytical framework. The Leavitt model consists of four interdependent elements—people, task, technology, and structure—where a change in any single element induces corresponding adjustments in the others. Therefore, systemic transformation manifests as the coordinated adaptation of multiple elements (Leavitt, 1965). Building on this foundation, the construction human–robot collaboration system can be understood as comprising diverse actors with different capabilities and requirements. With specific technologies and tools, they accomplish defined tasks within a given structural and institutional context. Ongoing advances in robotics have increasingly embedded robots within construction sites historically dominated by human labor. Tasks once executed solely by humans now proceed through human–robot collaboration, and organizational structures have reconfigured into diverse collaborative models. Taking these four elements as core variables, this study develops a sociotechnical framework that explains how human–robot collaboration drives the transformation of engineering management in construction. Through four interaction chains—technology–people, technology–task, structure–people, and structure–task—it reveals both the technological and social pathways through which human–robot collaboration drives engineering management transformation in construction, as illustrated in Fig. 3. Sections 3.1 and 3.2 elaborate on the new characteristics of engineering management emerging from the interactions among these variables, summarizing 15 key changes and outlining future research directions.

3.1 Engineering management transformation driven by technical subsystem evolution

3.1.1 Technical logic innovation through technology–task integration

Construction activities are organized around the process

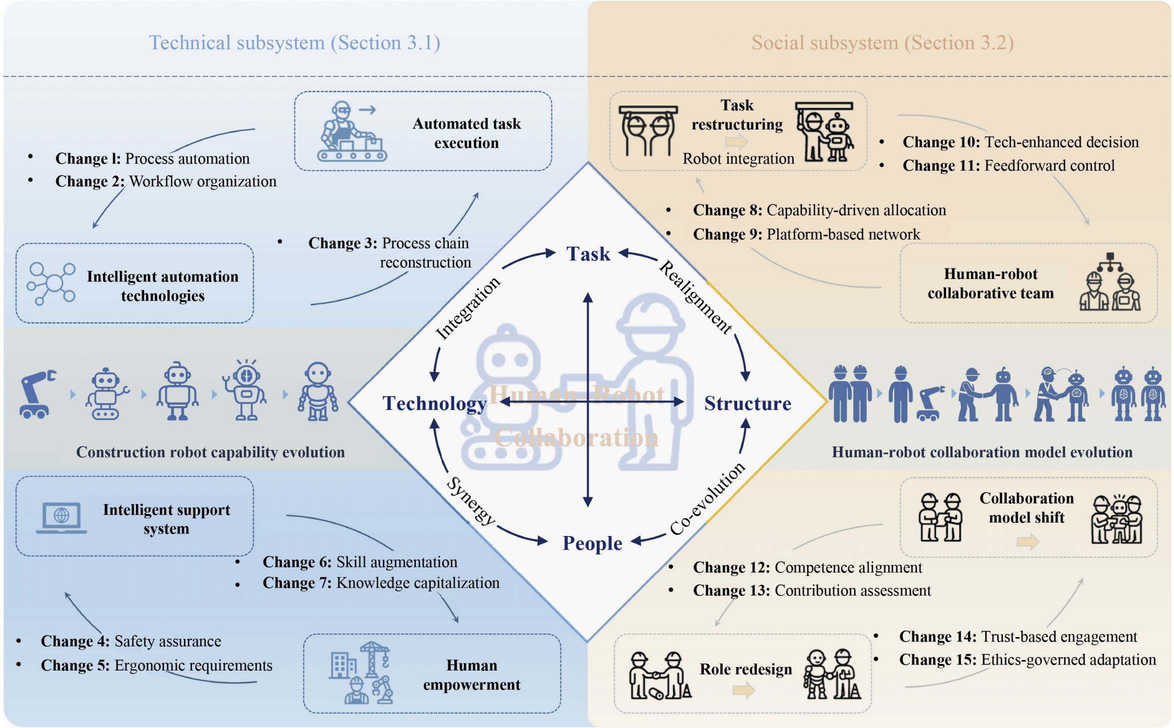

Fig. 3 A sociotechnical framework for engineering management transformation driven by human–robot collaboration.

chain, where each operation is systematically arranged under defined process constraints to complete the works from work subsections to the unit project. As robots and digital technologies enter the site, the technical logic of construction undergoes a fundamental shift that can be articulated across three progressive levels.

Change 1: Achieving a paradigm shift from “experience-based jugement” to “data-driven decision-making” at the construction process control level

(1) Precision and standardization in process execution

Robots are widely applied in key operations such as component positioning, assembly, and quality inspection. Through the integration of AI-powered perception and control systems, these robots facilitate highly precise operations and fully automated execution of repetitive tasks (Wang et al., 2025b). In unstructured and complex environments, robots equipped with simultaneous localization and mapping technologies can achieve millimeter-level object recognition and accurate handling of construction demolition debris, significantly reducing human-induced errors (Chen et al., 2022).

(2) Intelligent and efficient process control

Building Information Modeling (BIM), Internet of Things (IoTs), and AI technologies enable centralized management of data flows and execution logic across construction processes, enhancing the efficiency of scheduling and progress feedback (Lu et al., 2024). In parallel, process mining methods are applied to develop data-driven frameworks for workflow performance analysis in construction. This approach enables the identification of critical tasks, bottleneck monitoring, and real-time optimization (Martinez Lagunas and Nik-Bakht, 2024).

Change 2: Completing process reconfiguration from “linear serial connection” to “dynamic parallel integration” at the workflow organization level

(1) Seamless transition across task sequences

Digital twins enable real-time acquisition of on-site operation times and dynamic schedule updates, thereby aligning planned tasks with actual progress and markedly reducing process misalignment and idle time (Alsakka et al., 2024). In construction workflows involving multi-source and heterogeneous entities, a unified spatiotemporal framework is essential for precise synchronization across processes. The orthogonally synchronized model, coordinated via cyber-physical systems, improves temporal consistency under dynamic conditions and supports high-frequency coupling and collaborative execution among interdependent tasks (Jiang et al., 2022).

(2) Coordinated parallelism across multiple tasks

In an Industry 4.0 production line, a flexible job-shop scheduling model that couples mixed-integer linear programming with an enhanced genetic algorithm enables concurrent operation of multiple robots under limited-buffer and heterogeneous-machine constraints, shortening the overall makespan by about 34 % (Shakeri et al., 2025). At the microscale, up to 200 microrobots are trained with multi-agent reinforcement learning and counterfactual credit assignment. They cooperatively transport large payloads without centralized control, demonstrating robust and scalable swarm-level parallelism (Heuthe et al., 2024).

(3) Dynamic scheduling of task resources

Traditional process resource scheduling relies on static quotas, with work hours and labor allocation fixed in advance. With robots integrated as assignable resources and on-site sensing agents, telemetry from robots and IoT systems enables dynamic, pull-based scheduling that aligns planned work with real-time demand and site conditions. This reduces waiting, idle time, and rework in line with lean construction principles. A multi-agent scheduling framework based on deep reinforcement learning then provides real-time perception and joint optimization of task sequencing, robot dispatch and mode selection, human assignment, and buffer management, improving responsiveness to disruptions and variability (Liu et al., 2023).

Change 3: Advancing a new, integrated form of process chain reconstruction through technological convergence at the process-chain level

A new system of integrated construction processes, exemplified by 3D printing, is transforming traditionally sequential, multi-stage construction workflows into composite operational units that can be executed in a single integrated process (Sun et al., 2023). The construction 3D printing system integrates precision sensing, path planning, and control optimization to establish an integrated process platform that combines system control, quality evaluation, and collaborative operation (Xu et al., 2022).

3.1.2 Human empowerment through technology–people synergy

The empowerment brought by construction robotics and related technologies extends beyond optimizing workflows and improving productivity; it also enhances human well-being by mitigating workers’ operational risks and improving the working environment. Technology is being restructured around human safety and physical condition, shifting hazardous tasks toward remote operation to reduce project risks, while incorporating human factors such as fatigue and workload into resource scheduling. At the same time, standardization and demonstrative operations help lower the skill threshold for workers and transform experiential knowledge into reusable domain expertise.

Change 4: From hazardous operations to risk elimination through remote control

The introduction of robots and automated systems effectively reduces the need for workers to enter hazardous areas. Leveraging environmental perception and engineering control, these systems enable the unmanned execution of high-risk tasks, thereby eliminating risks at their source. A dual-rope-driven cleaning robot, for example, can autonomously move along building façades to perform high-altitude cleaning, effectively reducing the fall risk associated with façade operations (Chae et al., 2022). Where human involvement remains unavoidable, auxiliary technologies such as video monitoring can further limit workers' exposure. To address common fall hazards on construction sites, Ojha et al. (2023) proposed a multi-robot system that integrates path planning and visual recognition to autonomously inspect and localize indoor slipping and tripping risks.

Change 5: From efficiency orientation to human-factor-aware resource scheduling

In human–robot collaborative tasks, workers may face challenges such as cognitive overload or information fatigue. Accordingly, task design and allocation should prioritize not only performance and economic objectives but also human factors such as personality, cognitive capacity, and the broader process of meaning-making (Karakikes and Nathanael, 2023). Recent advances in human–robot collaboration research increasingly reflect a human-centered orientation, accounting for ergonomics, fatigue, cognition, intention, and comfort (Li et al., 2025). Human–robot task allocation further incorporates skill levels, spatial context, and fatigue states, employing multi-heuristic and greedy algorithms to achieve efficient and adaptive scheduling (Zeng et al., 2025).

Change 6: From craftsmanship dependence to deskilling of complex processes

Complex tasks that once depended on craftsmanship can be decomposed and standardized into action sequences amenable to perception, localization, and control through the integration of robots, sensors, and digital work orders. This shift lowers the entry barrier for frontline workers while improving quality consistency. Collaborative multi-arm robots can perform scaffold-free shell masonry, converting craftsmanship-intensive procedures into standardized, repeatable automated tasks and thus widening workforce participation (Bruun et al., 2024). Building on this shift, vision-guided welding robots identify weld seams in real time and adaptively adjust their trajectories, effectively encoding expert-level decisions into machine-executable logic and substituting for highly skilled manual labor in complex welding operations (Lee and Han, 2024).

Change 7: From experiential data to accumulation of domain knowledge as assets

Project knowledge has traditionally been transmitted through operational experience and individual memory, characterized by being unstructured, difficult to transfer, and highly dependent on personnel retention. With robots integrated into task execution, construction sites now generate large volumes of process data that can be systematically structured, including operation paths, collaboration logic, and parameter feedback. Acting simultaneously as data-collection interfaces and feedback agents, robotic systems encode, structure, and archive information in real time during execution, thereby continuously acquiring, reorganizing, and transferring task knowledge across the workflow (Meng et al., 2025). BIM, IoT, and knowledge graphs facilitate this transition by converting site experience into modular and reusable assets (Bai et al., 2025). To ensure accuracy and timeliness, knowledge quality is governed through evaluation metrics and completion strategies (Xue and Zou, 2023).

3.2 Engineering management transformation driven by social subsystem evolution

3.2.1 Managerial model reconfiguration through structure–task realignment

The mode of human–robot collaboration in construction determines how tasks are divided, assigned, and verified, directly shaping the management of project activities. As collaboration modes evolve, the organizational patterns of tasks undergo profound transformations in areas such as resource allocation, organizational structure, planning and decision-making, and supervision and control.

Change 8: Resource allocation from fixed-role assignment to the integrated scheduling of human–robot capabilities

Traditional workforce planning relies on job roles and trade classifications, where managers assign human workers to tasks based on predefined skill sets, forming a static mapping between labor categories and task demands. With robots increasingly deployed as autonomous task executors, scheduling logic is shifting from position-to-person matching toward capability-to-task alignment (Jia et al., 2025). Modern scheduling systems tend to integrate both human and robotic agents as composite capability units, dynamically assembling task teams based on operational needs. Robots are now capable of undertaking a significant share of repetitive tasks in construction workflows, thereby reducing manual workload and improving turnaround efficiency through automated feedback loops (Angelopoulos et al., 2024).

Change 9: Organizational structure from linear hierarchies to platform-driven collaborative networks

Conventional project organizations operate through rigid top-down chains of command, often leading to slow responses and fragmented information flow. In contrast, human–robot collaboration fosters a shift toward flatter, task-centric structures built on digital platforms. Coordination among managers, supervisors, and robots increasingly occurs through continuous data exchange rather than hierarchical instructions (Fu et al., 2024). Robots act as interactive nodes rather than passive tools, relaying real-time data on status and progress through BIM and IoT systems. This platform-based approach dissolves siloed units into modular, reconfigurable task networks, institutionalizing integrated collaboration among humans, machines, and digital platforms (Dixon et al., 2021).

Change 10: Planning and forecasting from human judgment to technology-augmented decision-making

Construction decisions such as task allocation and resource planning have long depended on managerial experience, often yielding delayed and opaque outcomes. With robots joining as active agents, decision-making is shifting toward human–machine co-creation. This shift requires restructuring decision logic through task division, cognitive coupling, and responsibility feedback (Xiong et al., 2022). Robots offer rule-based recommendations, while humans authorize key actions, enabling a move from centralized control to distributed consensus (Zhang et al., 2022). Through multidimensional modeling of on-site sensing data, historical project records, and external constraints, managers can perform risk prediction, resource optimization, and schedule simulation prior to task execution, significantly enhancing the foresight and accuracy of decision-making (Duan and Zou, 2025).

Change 11: Oversight and control from reactive supervision to feedforward control based on multi-source perception

In systems reliant on manual supervision, construction control is often delayed, depending on periodic patrols and after-the-fact inspections with limited responsiveness. As human–robot integration deepens, control rules become embedded in technical systems that autonomously sense and respond to changes. This shift enables real-time monitoring and timely intervention. Layered sensing architectures that integrate AI, sensor networks, and robotics continuously acquire multimodal site data. Machine learning models analyze data to detect deviations and risks early, generate control signals in advance, and dynamically adjust workflows and resource deployment (Abioye et al., 2021). In more complex scenarios, robots equipped with belief-space planning and active perception strategies select information-rich sensing actions, allowing for early detection and preemptive decision-making (Ragan et al., 2024).

3.2.2 Institutional restructuring through structure–people co-evolution

As human–robot collaboration evolves from a linear pattern of "human-led, robot-assisted" to a norm of "collaborative division and parallel complementarity," the governance of the "human" dimension in engineering management must undergo four parallel transitions—capability alignment, contribution evaluation, trust building, and ethical regulation.

Change 12: Role positioning and reskilling of capabilities

As collaborative modes evolve, construction workers are moving from traditional operators to proactive collaborators. Confronted with new technological requirements, workers need to update or acquire new skills and knowledge, engaging in a process of reskilling. Recent studies have identified the specific knowledge, skills, and competency elements required for workforce transformation in construction human–robot collaboration (Olukanni et al., 2025). Workers can accelerate capability growth by adopting an agile learning approach that emphasizes self-assessment and algorithm-supported feedback for continuous improvement. In parallel, leadership capability, organizational alignment, and well-designed training program have become key managerial competencies for deploying human resources in the era of intelligent construction (Deepa et al., 2024).

Change 13: Assessment of human–robot contribution and adjustment of incentives

Although terms such as "collaboration" and "co-working" are often used in industrial contexts to describe interactions between humans and robots and to suggest a form of partnership, the respective roles and contributions of humans and robots in the collaborative process should not be treated as equivalent (Callari et al., 2024). Recent studies have highlighted the diverse and often invisible workloads imposed on humans by robots, such as the continuous need to interpret, adjust, and optimize operations, rather than simply improving productivity or efficiency (Fischer and Frennert, 2025). Future performance measurement in engineering management should move beyond traditional labor-hour accounting toward a more comprehensive evaluation framework. It considers not only the individual contributions of human workers but also the synergistic effects of robots and automation systems, thereby enabling more accurate and equitable feedback and incentive mechanisms.

Change 14: Trust building and mechanism assurance in human–robot collaboration

Trust plays a crucial role in shaping the acceptance of human–robot interaction, influencing the extent to which human operators are willing to rely on the inputs or outputs provided by automated systems, particularly in hazardous or uncertain work environments (Charalambous et al., 2016). When humans engage with different types of robots and artificial intelligence tools, transparency becomes a key determinant of trust. Studies have shown that users often experience additional frustration and psychological stress when faced with opaque or ambiguous algorithmic management systems, which in turn undermines their trust in automation (Tarafdar et al., 2023). Future engineering management should require explainability, logging, and review of algorithmic and robotic outputs, and define human–machine decision boundaries and handover rules. An auditable, accountable, and measurable closed loop should be enforced to ensure reliable collaboration.

Change 15: Ethical guidelines and behavioral norms for collaboration

Robots are not merely tools but mediators of social relations; their deployment has the potential to reshape human values, identity, and patterns of social interaction. Ethical considerations should therefore encompass the promotion of human well-being, creativity, and social justice (Torras, 2024). The complexity of robot ethics demands interdisciplinary collaboration across engineering, philosophy, psychology, and sociology, and it requires frameworks that are both culturally responsive and globally applicable (Weng et al., 2025). The application of “accountability” and “liability” to AI-driven autonomous or semi-autonomous systems and to collaborative robots in particular has long been debated (Vecellio Segate and Daly, 2024). Looking ahead, engineering management must codify clear ethical standards and behavioral guidelines so that, as technology advances, rights and responsibilities between humans and robots are allocated in a fair, transparent, and accountable manner.

3.3 Potential research directions in engineering management for human–robot collaboration

Building on the preceding systematic analysis of the technical and social attributes of human–robot collaboration and the resulting paradigm shifts in engineering management, this paper proposes ten research directions that warrant further in-depth exploration.

(1) Re-definition of human–robot roles and task boundaries

How can human and robotic capabilities be quantitatively characterized under multi-dimensional task requirements to achieve optimal human–robot–task matching?

(2) Optimization of human–robot ratios and collaborative configurations

In varying operational contexts, how can differences in human and robotic capabilities be used to determine the optimal collaboration ratio and enable dynamic real-time reallocation?

(3) Efficiency in human–robot collaboration

How can key factors affecting operational efficiency be identified and modeled to achieve efficiency improvement, while taking into account constraints such as economic feasibility and technological maturity?

(4) Safety in human–robot collaboration

Under conditions of high task complexity, skill variability, and environmental uncertainty, how can human–robot configurations be designed to ensure both scientific rigor and operational safety?

(5) Balancing efficiency, resilience and development

Considering short-term efficiency gains, risk resilience, and long-term technological evolution, how should phased deployment and differentiated adjustment strategies for robotics be formulated?

(6) Organizational transformation and performance evaluation

In human–robot hybrid teams, how can workflows and organizational structures be reconfigured, and how should performance metrics be designed to evaluate the contributions of both humans and robots?

(7) Accountability and ethical boundaries

When failures or damages occur in human–robot collaborative systems, how can legal responsibilities and ethical obligations be delineated within the context of hybrid human–robot actions?

(8) Cross-industry integration and ecosystem building

How can robotic technologies be deeply integrated across the construction industry value chain to foster a new industrial ecosystem characterized by platform-based and modularized collaboration?

(9) Construction of domain-specific knowledge bases

Given the high heterogeneity of construction projects, how can process knowledge be standardized and extracted to support intelligent cross-project reuse and operational optimization?

(10) Design-oriented transformation of construction projects

How can site layout, workspace configuration, and project scheduling be redesigned to accommodate and optimize human–robot collaboration?

4 Conclusions and outlook

Human–robot collaboration in the construction industry is not a fixed reality but an evolving process shaped by the complex interaction between technical capabilities and social structures. From the dual perspectives of technology and society, this study conceptualizes human–robot collaboration in engineering management as a sociotechnical system composed of four interrelated variables: people, structure, technology, and task. The technological dimension determines how collaboration can be reliably achieved and stably operated, while the social dimension concerns how it can be effectively governed and institutionally expanded. The continuous coupling between these two dimensions indicates that human–robot collaboration is, in essence, a systemic process of symbiotic evolution rather than a simple juxtaposition of technology and society. The ultimate performance of collaboration depends on the compatibility between tasks and technologies, the clarity of roles and structures, and the interpretability and verifiability of interaction interfaces. Consequently, the transformation of engineering management should not be a passive response to technological change but an active strategic effort to design and adapt to a new sociotechnical equilibrium.

Future research and practice should move beyond single-objective optimization toward the systemic integration of technological and social dimensions. Key directions include developing dynamic metrics for human–robot capability assessment and task matching;

designing workspace layouts and scheduling systems; optimizing human–robot ratios and collaborative configurations; reconstructing performance evaluation frameworks for hybrid teams; establishing compliance architectures for data standards and interface protocols; advancing context-aware worker training that integrates human factors, safety, and well-being; and instituting auditing mechanisms that embed ethical and accountability boundaries, among others. Only when robots are recognized as active participants embedded within workflows and organizational structures can engineering management simultaneously enhance productivity and safety while achieving organizational evolution and sustainable development through human–robot collaboration.

Competing Interests The authors declare that they have no competing interests.

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