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SIX LEVELS OF ROBOTIC SUBSTITUTION OF HUMAN LABOUR: A STAGED FRAMEWORK FOR IMPROVING PERFORMANCE IN ENGINEERING ENTERPRISES*

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Abstract. Engineering enterprises face increasing pressure to improve productivity, quality, competitiveness and long-term sustainability under conditions of labour shortages, rising complexity and accelerating digital transformation. Robotic systems are often presented as a response to these pressures, yet the relationship between robotisation and enterprise performance is neither automatic nor uniform. Existing automation and autonomy frameworks classify system capability, while Industry 4.0 maturity models assess organisational readiness; however, they do not sufficiently explain how the progressive substitution of human labour by robotic systems can be linked to concrete performance outcomes. This paper addresses this gap by proposing a six-level framework of robotic substitution of human labour in engineering enterprises. The framework adopts work substitution as its central unit of analysis and distinguishes six stages: Assisted Work, Robot as a Helper, Human–Robot Tandem, Teleoperated Robotic Work, Semi-Autonomous Robotic Work and Full Robotic Autonomy. Each level is connected to specific performance mechanisms and indicators, including ergonomic load, safety, quality, overall equipment effectiveness (OEE), labour productivity, value added per employee and capital productivity. The framework is developed as a conceptual design artefact grounded in socio-technical systems thinking and illustrated through typical engineering operations such as welding, material handling, assembly, quality inspection and internal logistics. The paper argues that higher autonomy is not automatically superior; progression between levels should be governed by safety as a gatekeeper and operational data as an enabler. The framework provides managers with a structured language for performance-oriented, safe and evidence-based robotisation decisions.

Keywords: robotic substitution of human labour; engineering enterprises; manufacturing performance; productivity; competitiveness; Industry 4.0; human–robot collaboration; socio-technical systems; sustainable manufacturing

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1. Introduction

Engineering and manufacturing enterprises face increasing pressure to improve productivity, quality, competitiveness and long-term sustainability. In Europe, these pressures are intensified by labour and skills shortages: around four out of five small and medium-sized enterprises report difficulty finding workers with the required skills, while advanced-manufacturing sectors face ageing workforces and widening capability gaps (European Commission, 2024; CECIMO, 2025). At the same time, adoption is accelerating: average robot density in Western European manufacturing reached a record 267 units per 10,000 employees in 2024 (IFR,

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2025). Robotic systems are therefore increasingly viewed not only as technological innovations, but as strategic instruments for improving enterprise performance and reducing dependence on scarce manual labour.

However, robotisation does not automatically improve performance. Empirical research shows that the effects of advanced automation and Industry 4.0 technologies depend on implementation approach, production context, organisational capabilities and human capital rather than on technology alone (Krulický et al., 2024; Čižo et al., 2025; Bureš & Bartoš, 2025). A robot may improve repeatability but reduce flexibility; a collaborative robot may improve ergonomics but increase cycle time; a semi-autonomous system may improve throughput but require new supervision, maintenance and data capabilities. Robotisation should therefore be evaluated as a multidimensional performance intervention, not as a linear path toward higher autonomy. This contingency is consistent with recent competitiveness research showing that the effects of digital transformation vary with firms' underlying competitive capacity and organisational characteristics, rather than emerging uniformly from technology adoption itself (Pan et al., 2025).

Existing research provides valuable but partial perspectives. Levels-of-automation models explain how control is distributed between humans and machines (Endsley & Kaber, 1999; Parasuraman et al., 2000). Autonomy taxonomies such as SAE J3016 and ALFUS classify system capability (SAE International, 2018; Huang, 2008). Industry 4.0 maturity models assess organisational readiness, while safety and human–robot collaboration standards define interaction limits and protective requirements. However, these streams do not sufficiently explain how specific human tasks are progressively substituted or transformed by robotic systems, nor how such substitution translates into enterprise performance.

This creates a practical gap for managers of engineering enterprises. They must decide whether a unit of work should remain manual, be supported by an assistive device, be performed in cooperation with a robot, be teleoperated, be semi-autonomous or be fully autonomous. Each option implies different performance outcomes, safety requirements, data needs, human roles and governance responsibilities.

This paper addresses this gap by proposing a six-level framework of robotic substitution of human labour in engineering enterprises. The framework adopts work substitution as its unit of analysis and links each level to performance indicators such as ergonomic load, occupational safety, quality, overall equipment effectiveness (OEE), labour productivity, value added per employee and capital productivity. It is governed by two principles: safety acts as a gatekeeper of progression, and operational data act as an enabler of informed transition between levels. The framework does not assume that full autonomy is always desirable; remaining at a lower level may be rational when it provides a better balance between productivity, flexibility, quality, safety, cost and human capability.

The paper is guided by two research questions:

- *RQ1*: How can the stages of robotic substitution of human labour be structured so that each stage is linked to specific performance outcomes of an engineering enterprise?
- *RQ2*: What role do safety and the accumulation of operational data play as conditions governing progression between stages?

The remainder of the paper is organised as follows. Section 2 reviews the relevant literature. Section 3 defines the research gap and conceptual approach. Section 4 presents the six-level framework. Section 5 develops the performance logic and governing conditions. Section 6 illustrates the framework for typical engineering operations. Section 7 discusses managerial implications. Section 8 concludes with contributions, limitations and a research agenda

2. Literature Review

2.1 Digital transformation, Industry 4.0 and enterprise performance

Digital transformation and Industry 4.0 are widely associated with improved productivity, flexibility, quality and competitiveness in manufacturing enterprises. Their technological basis includes cyber-physical systems, industrial Internet of Things, sensors, simulation, cloud computing, advanced analytics, artificial intelligence

and robotics. In management-oriented research, these technologies are not only technical artefacts, but resources that can reshape value creation, business models, performance management and, at the network level, more sustainable and flexible production architectures.

However, empirical evidence shows that performance effects are contingent rather than automatic. Smart manufacturing maturity can improve financial performance and operational efficiency, but its effects depend on industry type and workforce structure (Jang et al., 2022). Industry 4.0 technologies can strengthen the relationship between servitisation and performance, but mainly when aligned with broader strategic transformation (Bortoluzzi et al., 2022). Human factors also matter: implementation is shaped by skills, fear, resistance and organisational readiness, not only by technological capability (Obermayer et al., 2022). Beyond technology adoption itself, organisational performance is shaped by the joint configuration of technology, leadership and human-resource practices.

Recent research on Industry 4.0, digital transformation and labour productivity similarly suggests that digital technologies support productivity, competitiveness and sustainability only when mediated by organisational conditions, data capabilities and human capital (Krulický et al., 2024; Čižo et al., 2025; Bureš & Bartoš, 2025). This literature establishes the first premise of the paper: digital and robotic technologies can contribute to enterprise performance, but only under specific contextual and organisational conditions. A complementary competitiveness perspective also identifies future readiness, knowledge, adaptive attitudes and regulatory frameworks as interdependent drivers of digital performance, supporting a holistic rather than isolated view of technological upgrading (Qazi, 2025).

Recent cross-sectoral studies further reinforce the view that the business value of digital technologies depends on organisational readiness and systematic evaluation rather than on technology adoption alone. Skare et al. (2026) developed a three-stage information-analytical system that evaluates the feasibility of artificial intelligence adoption, managers' understanding of its implementation and its potential contribution to sustainable business outcomes, based on data from 1,000 Slovak enterprises. From complementary sectoral perspectives, Gavurova et al. (2025) proposed a hybrid decision-support model combining stakeholder assessments and expert knowledge to evaluate the socio-economic effects of digital transformation, while Smolanka et al. (2024) developed an expert model for measuring and managing the level of information-technology implementation in healthcare institutions. Although these studies focus on different economic sectors, they collectively demonstrate that technological transformation requires context-sensitive, multidimensional and evidence-based evaluation frameworks – a principle that is directly relevant to performance-oriented robotic substitution in engineering enterprises.

2.2 Robotisation of manufacturing work

Robotisation is a specific form of digital transformation because robots physically intervene in the execution of work. Unlike many digital technologies, they alter not only information flows but also physical tasks, work organisation, safety conditions, skill requirements and the relationship between humans and machines on the shop floor.

Stingl et al. (2024) conceptualise robotised manufacturing work as a complex system of entangled changes involving work, organisation of labour, workers' experiences and the firm's environment. This systemic view is important because robotisation cannot be reduced to a linear cause-effect relationship between robot adoption and performance improvement. Anzolin and Andreoni (2023) further show that firms robotise in heterogeneous ways depending on production modularity, technology flexibility and product-design stability. Even within the same sector, robotisation differs according to how technology is integrated into the production system. Evidence from robotic process automation similarly indicates that successful deployment is determined less by the technology itself than by implementation approach, organisational readiness and clearly defined success factors.

These findings support the paper's focus on work substitution. Robotisation should not be understood as simple replacement of a worker by a machine. When a robot takes over part of a task, surrounding human roles, coordination mechanisms, data flows, safety requirements and managerial responsibilities also change. In many cases, workers are not removed from the system but repositioned toward preparation, supervision, exception

handling, maintenance, quality control or process improvement. This staged perspective is also consistent with evidence from production enterprises showing that successful corporate change depends on clearly defined objectives, regular monitoring, implementation data and systematic tracking of incremental progress (Vrtana et al., 2025).

2.3 Contingent performance effects of robotisation

The performance effects of robotisation are multidimensional and contingent. Robots may improve repeatability, precision, safety or throughput, but they may also reduce flexibility, increase capital intensity, require new skills or introduce new coordination and safety risks. Therefore, robotisation should not be evaluated as a general move toward higher autonomy, but as a performance intervention whose value depends on task characteristics and organisational conditions.

This contingency is consistent with evidence from smart manufacturing and Industry 4.0 adoption (Jang et al., 2022; Bortoluzzi et al., 2022). It is also visible in lean production contexts, where Industry 4.0 technologies may generate tensions between managerial expectations, worker roles and established improvement routines (Margherita & Braccini, 2024). Such tensions show that technology adoption is also an organisational change process.

For engineering enterprises, this implies that performance must be assessed across several dimensions: productivity, quality, OEE, lead time, unit cost, safety, ergonomic load, flexibility, value added per employee, reliability, energy use and human-capital development. A higher level of robotic substitution should be considered better only if it improves the performance dimensions that matter for the specific enterprise without creating unacceptable safety, organisational or economic costs. More broadly, recent European evidence links the prevalence of high-growth firms in digitally transforming environments to labour-market efficiency, business sophistication, market size and access to finance, underscoring that technology-related performance is embedded in a wider competitiveness configuration (del Olmo-García et al., 2025).

2.4 Automation, autonomy and maturity frameworks

Existing automation, autonomy and maturity frameworks provide useful foundations but do not fully address the managerial problem studied here. Levels-of-automation models describe how control and decision-making are distributed between humans and machines (Parasuraman et al., 2000; Endsley & Kaber, 1999). They show that automation is not binary and that human-machine responsibility can be distributed in different ways. However, they do not link levels of work substitution to enterprise performance outcomes.

Autonomy taxonomies such as SAE J3016 and ALFUS demonstrate the communicative value of staged models (SAE International, 2018; Huang, 2008). Yet they classify system capability rather than the transformation of concrete human work. Industry 4.0 maturity models, in turn, assess organisational readiness, connectivity and data infrastructure, but usually operate at the level of the firm or production system as a whole. They do not specify how individual tasks are progressively substituted or transformed.

The limitation is therefore one of unit of analysis. Existing frameworks ask how control is distributed, what a system can do, or how digitally mature an organisation is. This paper asks a different question: how can progressive robotic substitution of human labour be structured so that each stage is linked to enterprise performance and governed by safety and data conditions?

2.5 Safety, human–robot collaboration and socio-technical governance

Safety and human factors are central to robotic substitution. Standards such as ISO 10218 and ISO/TS 15066 define interaction modes, separation requirements, speed and force limits, and protective measures for industrial and collaborative robots. These standards are essential, but in a staged framework safety should be treated not only as compliance, but as a transition condition.

Human–robot collaboration (HRC) illustrates this point. Collaborative robots can combine human flexibility with robotic precision and repeatability, but their performance effects are not straightforward. They may improve ergonomics and quality while also introducing coordination costs, cycle-time penalties, cognitive load

or resistance. Worker adaptation is therefore critical. Employees working with robots face technical issues, skill gaps and changing responsibilities, and their roles often shift from direct execution toward supervision and exception handling (Salcedo-Gil et al., 2025). Regional and organisational perceptions also matter, especially in Central and Eastern Europe, where robotics is associated with workflow automation, safety, profitability and workforce retention (Stor et al., 2025).

Robotisation may generate concerns about job substitution, but its social meaning is not always negative. Technological innovation can also signal firm health and long-term competitiveness, reducing perceived job insecurity among remaining workers under certain conditions (Caselli et al., 2024). Overall, safety, adaptation and governance determine whether robotic substitution becomes a sustainable performance improvement or a premature technological intervention.

2.6 Literature synthesis

The reviewed literature provides five building blocks. Industry 4.0 research shows that digital technologies can support performance, but their effects depend on organisational and human conditions. Robotisation research shows that manufacturing work is transformed as a socio-technical system. Performance studies show that automation effects are contingent and involve trade-offs. Autonomy and maturity frameworks provide staged thinking, but focus on system capability or organisational readiness. Safety and HRC research shows that progression toward higher robotic involvement must be governed by safety, adaptation and responsibility.

What remains missing is an integrated framework that treats robotic substitution of human labour as the central unit of analysis and links different stages of substitution to specific enterprise performance outcomes. This gap is practically important because managers do not decide about autonomy in the abstract. They decide whether a concrete task should remain manual, be assisted, be shared with a robot, be teleoperated, be semi-autonomous or be fully autonomous. The present study addresses this gap by proposing a six-level framework that connects each stage to performance outcomes and defines safety and operational data as governing conditions for progression.

3. Research Gap and Conceptual Approach

The literature shows that robotisation, Industry 4.0 and automation are well-established research themes, but they remain insufficiently integrated from the perspective of managerial decision-making. Automation frameworks classify control allocation, autonomy taxonomies classify system capability, maturity models assess organisational readiness, and safety standards define interaction constraints. None of these approaches adopts progressive work substitution as its central unit of analysis.

This creates a practical and conceptual gap. Managers of engineering enterprises do not decide about autonomy in the abstract. They decide whether specific tasks or task segments should remain manual, be supported by robots, be performed collaboratively, be teleoperated, be conditionally automated or be fully substituted. Each option implies different performance outcomes, safety requirements, data needs, human roles and governance responsibilities. A technically feasible robotic solution may still be economically unjustified, unsafe, too rigid for customer-specific production or dependent on capabilities that the firm does not yet possess.

To address this gap, the paper adopts work substitution as the central unit of analysis. Work substitution is understood as the progressive transfer, transformation or reallocation of responsibility for task execution, physical action, monitoring, decision support or exception handling from humans to robotic systems. This perspective differs from system autonomy because it starts not with what the robot can do technically, but with which elements of human work are being changed and what this means for enterprise performance.

The conceptual approach is grounded in socio-technical systems thinking, which emphasises the joint configuration of technical artefacts, human roles and organisational processes (Trist & Bamforth, 1951; Checkland, 1985). From this perspective, each level of robotic substitution represents a socio-technical configuration in which robotic capability, human responsibility, safety assumptions, operational data and performance indicators must be aligned.

The framework is developed as a conceptual design artefact following the logic of design science research, where artefacts are created to address relevant organisational problems and support structured problem-solving (Hevner et al., 2004; Peffers et al., 2007). Its purpose is not to predict performance outcomes statistically, but to provide a structured language for analysing and managing staged robotic substitution in engineering enterprises.

Three assumptions shape the proposed framework. First, robotic substitution is staged rather than binary: human labour is progressively supported, shared, supervised, transferred or transformed across different configurations. Second, performance is multidimensional and contingent: the value of a substitution level depends on the indicators that matter in the given enterprise context and on whether benefits outweigh safety, organisational and economic costs. Third, progression is conditional: a higher level of substitution is justified only when safety requirements are met, operational data reduce uncertainty, and governance responsibilities are clearly defined. This staged and conditional view is consistent with conceptual accounts of digital transformation that describe enterprise development as a path punctuated by qualitative transition points rather than continuous change.

The contribution of this paper is therefore to reframe robotisation as a staged, safety-governed and data-enabled transformation of work. Whereas existing automation frameworks classify levels of control and maturity models classify organisational readiness, this study classifies levels of work substitution and links them to enterprise performance. The following section presents the proposed six-level framework.

4. Conceptual Framework: Six Levels of Robotic Substitution

This section presents the proposed six-level framework of robotic substitution of human labour in engineering enterprises. The framework classifies how human-performed work can be progressively supported, shared, transferred or substituted by robotic systems. Its central unit of analysis is not the robot as a technical system, but the unit of work being transformed. A unit of work may refer to a task, task segment, workstation activity, production operation or recurring role, such as material handling, welding preparation, machine loading, assembly support, quality inspection or internal logistics.

The framework distinguishes six levels of robotic substitution. Its staged logic builds on levels-of-automation and autonomy frameworks, but shifts the unit of analysis from system capability to work substitution and enterprise performance (Parasuraman et al., 2000; SAE International, 2018). Each level represents a relatively stable socio-technical configuration in which robot role, human role, safety paradigm, data requirements and performance logic are aligned. Progression between levels is conditional rather than automatic. Higher levels require stronger safety assurance, richer operational data, clearer governance and a stronger business case. Therefore, Level 6 is not treated as a universal target; in many engineering enterprises, an intermediate level may provide the best performance fit.

At **Level 1 — Assisted Work**, the human worker remains the primary executor and decision-maker, while robotic, mechatronic or wearable systems provide passive or semi-passive assistance. Examples include passive exoskeletons, lifting assistance, ergonomic supports, positioning aids or wearable guidance systems. The performance contribution is mainly improvement of human work conditions rather than labour substitution. Key indicators include ergonomic load, fatigue, injury risk, absenteeism, worker acceptance and stability of manual performance.

At **Level 2 — Robot as a Helper**, the robot performs simple auxiliary tasks, usually separated from the human in space, time or responsibility. The human continues to perform the core value-adding task, while the robot supports transport, feeding, positioning, sorting, preparation or repetitive movement. The performance contribution is reduction of non-value-adding work, such as walking, waiting, handling or internal transport. Safety is typically ensured through separation, predefined routes, restricted movement and procedural controls.

At **Level 3 — Human–Robot Tandem**, humans and robots operate in the same process or workspace and jointly contribute to task execution. The robot actively participates in production work, while the human remains responsible for judgement, correction, quality and exceptions. Examples include collaborative assembly, robotic positioning, cobot-assisted manipulation or collaborative inspection. The performance logic is complementarity: human flexibility and judgement are combined with robotic precision, repeatability or strength. This level corresponds to HRC; the terms Human–Robot Tandem and HRC are used interchangeably

in this paper. Performance at this level depends on task allocation, interaction design and controlled physical interaction (ISO/TS 15066; Onnasch et al., 2014).

At **Level 4 — Teleoperated Robotic Work**, the robot performs the physical task remotely under continuous or on-demand human control. The human is no longer co-located with the work process but retains decision-making authority. This level is relevant where human judgement remains necessary but direct human presence is undesirable, dangerous or inefficient, such as remote inspection, hazardous handling or maintenance in restricted spaces. The performance contribution lies in separating human expertise from physical exposure.

At **Level 5 — Semi-Autonomous Robotic Work**, the robot performs the task autonomously under predefined normal conditions, while humans supervise and intervene only in exceptions. The robot is expected to execute the task, monitor its own state, detect anomalies and request human support when uncertainty exceeds acceptable limits. Examples include robotic machine loading, autonomous internal transport with exception escalation, robotic welding of standardised parts or automated inspection with human review of uncertain cases. This level can generate substantial productivity gains, but requires reliable perception, decision logging, exception management and governance.

At **Level 6 — Full Robotic Autonomy**, the robot fully substitutes human labour for a defined task, role or process within a defined operating envelope, i.e. the specified range of conditions under which safe and reliable operation is assured. Human involvement is limited to strategic oversight, system maintenance, periodic auditing and long-term governance. Examples include fully autonomous production cells, lights-out (fully unmanned) machining, autonomous quality-control loops or automated storage and retrieval systems. Level 6 should be defined only for a specific task or operational domain, not for the enterprise as a whole. Its performance logic is based on high repeatability, scalability, labour independence, uptime and long-term reliability. OEE is particularly relevant where robotic substitution affects availability, performance rate and quality losses in production equipment (Nakajima, 1988). Table 1 summarises the six-level framework.

Table 1. Six levels of robotic substitution of human labour in engineering enterprises

Level	Name	Robot's role	Human role	Typical performance contribution	Key performance indicators
1	Assisted Work	Passive or semi-passive support	Full execution and decision-making	Reduced physical or cognitive burden	Ergonomic load, fatigue, injury risk, absenteeism, acceptance
2	Robot as a Helper	Execution of simple auxiliary tasks	Core task execution and coordination	Reduction of non-value-adding work	Walking distance, waiting time, handling effort, task reliability, labour utilisation
3	Human–Robot Tandem	Active participation in shared task execution	Collaboration, judgement, correction and responsibility	Complementarity of human flexibility and robotic repeatability	Defect rate, rework, ergonomic load, cycle-time stability, human interventions
4	Teleoperated Robotic Work	Remote physical execution under human control	Remote decision-making and control	Separation of human judgement from hazardous or distant physical work	Hazard exposure, downtime, response time, latency tolerance, intervention logs
5	Semi-Autonomous Robotic Work	Conditional autonomous execution under normal conditions	Supervision and exception handling	Scalable execution with human oversight	OEE, throughput, intervention frequency, exception rate, quality stability, mean time between failures (MTBF), value added per employee
6	Full Robotic Autonomy	Full execution within defined operating envelope	Strategic oversight, maintenance and audit	High repeatability, labour independence and system-level performance	OEE, unit cost, capital productivity, uptime, rare-event frequency, long-term reliability, value added per employee

The framework can be used both analytically and managerially. Analytically, it classifies the current state of robotisation for a given task or process. Managerially, it supports decisions about whether progression to a higher level is desirable, feasible and justified.

Progression between levels is governed by four transition gates: capability, safety, data and organisational governance. The capability gate asks whether the robotic system can reliably perform the target function. The safety gate asks whether the configuration can be deployed without unacceptable risk. The data gate asks

whether sufficient operational evidence exists to support the transition. The governance gate asks whether roles, responsibilities, escalation procedures and accountability mechanisms are defined. This transition-gate logic extends capability-oriented autonomy frameworks by adding safety, data and governance conditions as prerequisites for progression (Huang, 2008; ISO 10218; ISO/TS 15066). Table 2 summarises the transition logic.

Table 2. Transition gates between levels of robotic substitution

Transition	Capability gate	Safety gate	Data gate	Governance gate
Level 1 → Level 2	Assistance is stable and task segments suitable for robotic support are identified	No new active hazards are introduced	Evidence of load reduction and task variability	Task ownership, basic risk assessment and operator training are defined
Level 2 → Level 3	Robot behaviour is predictable near humans and can be integrated into shared workflow	Shared-space operation is validated through speed, force, collision and stop controls	Incident-free operation, stable task boundaries and intervention records are available	HRC procedures, responsibility model and safety validation are defined
Level 3 → Level 4	Task can be executed without co-located human presence	Communication loss, latency and fail-safe behaviour are addressed	Human interventions, corrections and latency tolerance are documented	Remote operation roles, authority and monitoring infrastructure are defined
Level 4 → Level 5	Routine decisions can be delegated to the system under normal conditions	Robot behaves conservatively under uncertainty and requests help in exceptions	Decision logs, intervention patterns and exception taxonomy are available	Supervision model, escalation protocols and AI risk management are defined
Level 5 → Level 6	System can handle expected scenarios within the defined operating envelope	Intrinsic safety is assured without real-time human fallback	Long-term stability, rare-event analysis and auditable decision traces are available	Liability, audit, maintenance and continuous review mechanisms are defined

The transition gates prevent the framework from becoming a purely technological ladder. A firm should not progress to a higher level simply because the technology exists. Progression is justified only when capability, safety, data and governance are aligned with the enterprise's performance objectives.

5. Performance Logic and Governing Conditions

The six-level framework becomes managerially useful only when levels of substitution are connected to enterprise performance. The central argument is that robotic substitution should not be evaluated by autonomy alone. Higher autonomy may increase throughput, reduce labour dependency and improve repeatability, but it may also increase capital intensity, maintenance complexity, safety requirements, coordination costs and organisational risk. The performance value of a given level therefore depends on the task, production context, strategic priorities and readiness of the socio-technical system.

5.1 Multidimensional performance

In engineering enterprises, performance is multidimensional. A robotic system may reduce manual labour while increasing downtime, improve throughput while reducing flexibility, or reduce ergonomic strain without improving cycle time. For this reason, robotic substitution should be assessed through a balanced set of indicators.

The main dimensions are operational performance, quality performance, labour and human-capital performance, safety and risk performance, economic and strategic performance, and sustainability performance. Operational performance includes cycle time, throughput, OEE, lead time, downtime and process reliability. Quality performance includes repeatability, defect rate, rework, first-pass yield and inspection consistency. Labour and human-capital performance includes labour productivity, value added per employee, skill utilisation, ergonomic load, fatigue, absenteeism and retention. Safety and risk performance includes accident risk, near-misses, hazardous exposure and clarity of responsibility. Economic and strategic performance includes unit cost, return

on investment (ROI), capital productivity, scalability and customer responsiveness. Sustainability performance includes resource efficiency, workplace safety, waste reduction and long-term workforce sustainability.

This multidimensional perspective is essential because each substitution level creates value differently. Lower levels often improve ergonomics, safety and workforce sustainability. Intermediate levels reduce non-value-adding work, combine human judgement with robotic repeatability, or separate human expertise from hazardous exposure. Higher levels may improve throughput, OEE, labour productivity, quality stability, unit cost and capital productivity. A higher level is therefore not automatically better; it simply changes the performance profile. Higher levels of robotisation have also been linked, albeit non-linearly, to corporate environmental performance and to a shift of workers toward higher value-added activities, connecting substitution to environmental and social sustainability (Zhu et al., 2024; Luan et al., 2025).

5.2 Trade-offs in robotic substitution

A core principle of the framework is that higher autonomy is not automatically superior. The optimal level of robotic substitution is the level that creates the best balance between performance benefits and transition costs under specific enterprise conditions.

Several trade-offs are particularly important. The productivity–flexibility trade-off arises because highly automated systems can be efficient in repetitive and stable processes, but may be too rigid for customer-specific or low-volume engineering production. The speed–quality–safety trade-off appears when increasing robotic speed improves throughput but creates additional safety constraints or makes recovery from errors more difficult. The labour-saving–capability-building trade-off means that reducing direct manual labour often creates new requirements for programming, maintenance, supervision, data analysis and process engineering. The standardisation–learning trade-off is relevant because higher autonomy requires stable operating envelopes, while many engineering processes contain variability that is still understood mainly through human experience. Finally, the capital-productivity trade-off arises when high fixed investment improves performance only under sufficient utilisation and process stability.

These trade-offs explain why remaining at a lower or intermediate level may be rational. A Level 3 human–robot tandem may outperform Level 5 conditional autonomy when the task requires frequent judgement and adaptation. A Level 1 assistive solution may be more valuable than a complex robot if the main performance problem is fatigue, injury risk or workforce retention. A Level 2 helper robot may generate strong benefits by removing non-value-adding work without redesigning the core process. The framework therefore does not prescribe a universal path toward full autonomy; it supports selection of the substitution level that best fits the enterprise’s performance logic.

5.3 Safety, data and governance as progression conditions

Progression between levels should be governed by three conditions: safety, data and governance.

Safety acts as a gatekeeper. A higher level of substitution is permissible only if the target configuration can be deployed without unacceptable risk. At lower levels, safety is mainly associated with ergonomic design, mechanical constraints and separation. At collaborative levels, it becomes part of shared work design, including speed and force limits, collision detection, safe-stop behaviour and clear responsibility. At semi-autonomous and autonomous levels, safety depends increasingly on robustness, perception, uncertainty management, exception handling and intrinsic safe behaviour within the defined operating envelope. The absence of a sufficient safety case is therefore a legitimate reason to remain at a lower level. Empirical risk analysis in custom-manufacturing engineering settings confirms that automation does not automatically reduce operational risk, which reinforces the role of safety as an explicit gate rather than an assumed by-product of robotisation.

Operational data act as an enabler. Each level should generate evidence that reduces uncertainty and supports informed progression. Assisted work generates ergonomic and human-factor data. Helper robots generate reliability and task-standardisation data. Human–robot tandem work generates interaction data, corrections, near-misses and contextual cues. Teleoperated work generates intervention and failure-mode data. Semi-autonomous systems generate decision logs, exception patterns and uncertainty estimates. Full autonomy requires long-term monitoring, audit trails and rare-event analysis. Lower levels are therefore not only

operational states; they are learning environments. Treating accumulated operational data as a strategic asset is consistent with evidence that big-data-supported decision-making contributes to the economic sustainability of enterprises. Governance ensures that capability, safety and data are translated into responsible action. Progression requires ownership of the process, clear responsibilities, escalation procedures, training, maintenance capability, vendor management, cybersecurity, data governance and continuous review. This is especially important at higher levels, where humans no longer directly execute the task. Responsibility does not disappear when work is delegated to a robot; it shifts to system design, supervision, maintenance, monitoring and organisational accountability.

5.4 Summary

The performance logic of the framework can be summarised in three propositions. First, each level of robotic substitution creates value through a different mechanism and must be evaluated through different performance indicators. Second, higher autonomy is not automatically better; the optimal level depends on the balance between performance benefits, safety requirements, data maturity and organisational costs. Third, progression between levels must be governed by safety, operational data and organisational readiness.

This turns the six-level framework from a classification tool into a managerial decision model. It helps engineering enterprises ask not only what level of robotisation is technically possible, but which level is performance-relevant, safe, evidence-based and governable in their specific context.

6. Illustrative Mapping for Engineering Enterprises

The framework can be applied to different types of engineering work, but its managerial value becomes clearer when it is mapped onto concrete operations. This section illustrates its use in five typical engineering-enterprise contexts: welding, material handling, assembly, quality inspection and internal logistics. The purpose is not empirical validation, but demonstration of how the framework supports structured reasoning about appropriate substitution levels for specific units of work.

Engineering enterprises combine repetitive operations, skilled manual work, product variability, customer-specific requirements and safety-critical tasks. This diversity makes one-step automation unrealistic in many cases. Some operations may justify high levels of substitution because they are repetitive, standardised and data-rich. Others may remain at lower levels because human judgement, flexibility or safety constraints remain central. Table 3 summarises this mapping.

Table 3. Illustrative mapping of engineering operations to likely substitution levels

Operation	Lower-level substitution logic	Intermediate-level substitution logic	Higher-level substitution logic	Main constraints
Welding	Positioning aids, lifting devices, fume extraction or ergonomic supports reduce physical strain and exposure	Human–robot tandem welding, robotic positioning or selected robotic weld paths while human judgement and quality decisions remain central	Semi-autonomous or autonomous welding of standardised product families with stable fixtures and validated parameters	Part variability, fixture quality, weld-path repeatability, inspection requirements, safety
Material handling	Lifting aids, manipulators, balancers or exoskeletons reduce physical load while human control remains dominant	Robot-as-helper or collaborative handling reduces walking, waiting, transport and repetitive manipulation	Autonomous handling, palletising, machine loading or robotic transfer in structured environments	Object variability, gripping reliability, route stability, identification accuracy
Assembly	Guided work, ergonomic fixtures, visual instructions and part presentation support manual assembly	Human–robot tandem assembly, robotic fastening, holding or positioning while humans manage alignment and sequencing	Semi-autonomous assembly of stable product families with controlled tolerances and reliable sensing	Product variety, tolerances, dexterity, sequencing, tacit knowledge
Quality inspection	Digital checklists, measurement aids and visual guidance support human inspection	Robotic measurement or scanning combined with human interpretation of borderline cases	Automated inspection, AI-supported defect classification and closed-loop quality feedback	False positives/negatives, customer requirements, traceability, auditability

Internal logistics	Ergonomic picking aids, wearable scanners, visual guidance or lifting devices support operators	Transport assisted by autonomous mobile robots (AMR), shared logistics workflows and robot-as-helper material delivery	Semi-autonomous or autonomous material flow integrated with enterprise resource planning (ERP), manufacturing execution (MES) or warehouse management (WMS) systems	Layout stability, load standardisation, localisation, system integration
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The mapping shows that different engineering operations naturally align with different substitution levels. Material handling and internal logistics often progress more easily toward higher levels because tasks can be standardised, routes can be controlled and performance indicators are measurable. Welding and quality inspection may reach high levels in stable product families, but often require human judgement for variation, interpretation and exception handling. Assembly is frequently the most sensitive to product variability and tacit skill, making Levels 2 and 3 particularly relevant in many customer-specific engineering environments.

The key implication is that the appropriate level is operation-specific. A single enterprise may simultaneously operate Level 6 in selected logistics loops, Level 5 in machine loading, Level 3 in assembly, Level 2 in material preparation and Level 1 in specialised manual work. The framework should therefore not be used to classify the digital maturity of the firm as a whole. It should be used to classify and manage substitution levels for specific units of work.

Illustrative mapping also helps managers decide where progression is valuable, premature or unnecessary. It shows that full autonomy should not be treated as the universal objective: a collaborative assembly cell may be more valuable than a rigid automated cell if product variety is high, while an assistive welding device may be more rational than a robotic welding cell if volumes are low and variability is high. In addition, each level guides data collection: assisted work generates ergonomic data, helper tasks generate reliability data, collaborative work generates interaction data, teleoperation generates intervention data, semi-autonomous work generates decision logs and full autonomy requires audit data.

In this sense, the framework functions as a practical diagnostic tool. It helps engineering enterprises identify where robotic substitution is feasible, where it is valuable, where it is unsafe or premature, and where lower levels of substitution may remain strategically appropriate.

7. Managerial Implications

The proposed framework reframes robotisation from a technology-acquisition problem into a performance-oriented work-design decision. Instead of asking whether the firm should “automate more”, managers can ask which units of work should be supported, shared, remotely controlled, semi-autonomously executed or fully substituted, and under what performance, safety, data and governance conditions.

First, robotisation should be assessed at the level of concrete work units, not at the level of the enterprise as a whole. Engineering enterprises rarely become automated uniformly. A single firm may operate autonomous internal logistics in one area, collaborative assembly in another, assisted manual welding elsewhere, and semi-autonomous inspection for selected product families. The framework therefore functions as a task-level diagnostic tool: each relevant task, workstation or operation can be mapped to one of the six levels. This helps managers identify where the firm is under-automated, over-automated or prematurely automated.

Second, managers should start from the performance problem rather than from the robot. If the problem is ergonomic strain or workforce sustainability, Level 1 or Level 3 may be sufficient. If the problem is waiting time, walking distance or material availability, Level 2 may provide the most efficient improvement. If the problem is hazardous exposure, Level 4 may be appropriate. If the problem is throughput and repeatability in a stable process, Level 5 or Level 6 may become relevant. This performance-first logic helps prevent technology-driven overinvestment.

Third, lower levels of substitution should be treated as legitimate strategic choices. Remaining at Level 1, 2 or 3 is not necessarily a failure of innovation. Assisted work may be optimal when human skill remains essential but physical load threatens workforce sustainability. A robot-as-helper configuration may remove non-value-adding work without disrupting the core process. A human–robot tandem may preserve human judgement while improving precision, quality or ergonomics. These configurations can be strategically superior to higher autonomy when tasks are variable, volumes are unstable or the cost of standardisation is too high.

Fourth, robotisation should be governed as a portfolio of substitution levels. Different operations should be assigned different target levels according to task characteristics, performance potential and transition readiness. Some tasks should remain human-centred; some are suitable for assistance or helper automation; others should develop through collaborative or teleoperated configurations to generate data and reduce uncertainty; and a smaller set of stable, high-volume tasks may justify semi-autonomous or fully autonomous solutions. This portfolio logic supports strategic prioritisation and helps build a staged robotisation roadmap. Such roadmaps may also be aligned with external enablers, including European policy instruments supporting Industry 4.0 investments and the broader role of automation in reshoring production activities within the European Union (Xu et al., 2026).

Fifth, transition gates should be embedded into investment decisions. Before progressing to a higher level, managers should ask: Can the system perform the target function reliably? Can the configuration be deployed without unacceptable risk? Is there sufficient operational evidence to justify the transition? Are roles, responsibilities, escalation procedures and accountability mechanisms defined? These questions prevent automation projects from being evaluated only through ROI or technical feasibility. A project may have an attractive payback period but still be premature if the process is unstable, safety cannot be assured or the organisation lacks supervision and maintenance capability.

Finally, the framework highlights safety, data and human capabilities as strategic assets. Safety capability includes risk assessment, compliance with standards, incident learning and clear accountability. Data capability means collecting structured evidence about task variability, interventions, defects, downtime, near-misses and exception cases. Human capability is equally important because substitution changes work roles: as autonomy increases, humans move from direct execution toward supervision, exception handling, maintenance, programming, data interpretation and governance.

The framework also improves communication with employees, top management and suppliers. Internally, it clarifies that robotisation does not always mean replacing humans: Level 2 removes transport or preparation tasks, Level 3 requires cooperation, and Level 5 shifts the operator's role toward supervision. For top management, it translates robotisation into performance language such as OEE, quality, safety, labour productivity, flexibility and capital productivity. For suppliers, it provides a structured language for requirements, acceptance criteria and performance evaluation.

In summary, the framework helps engineering enterprises avoid both technological conservatism and automation determinism. It supports an approach that is ambitious enough to use robotics for productivity, quality and sustainability, but disciplined enough to recognise when higher autonomy is unsafe, uneconomic or organisationally premature.

8. Conclusions

This paper addressed the question of how robotic systems can contribute to performance improvement in engineering enterprises when the relationship between robotisation and performance is neither automatic nor uniform. Existing literature provides useful insights into automation levels, autonomy taxonomies, Industry 4.0 maturity, safety standards and human–robot collaboration, but these streams do not sufficiently explain how progressive substitution of human labour can be structured as a performance-oriented managerial process.

The paper responds by proposing a six-level framework of robotic substitution of human labour. The framework shifts the unit of analysis from system autonomy to work substitution. Instead of asking how autonomous a

robot is in technical terms, it asks which elements of human work are being supported, shared, remotely controlled, conditionally automated or fully substituted, and under what performance, safety, data and governance conditions.

The first research question asked how the stages of robotic substitution can be structured so that each stage is linked to specific performance outcomes. The answer is provided through six levels: Assisted Work, Robot as a Helper, Human–Robot Tandem, Teleoperated Robotic Work, Semi-Autonomous Robotic Work and Full Robotic Autonomy. Lower levels mainly contribute through ergonomics, safety and workforce sustainability; intermediate levels through reduction of non-value-adding work, complementarity and hazardous-exposure reduction; and higher levels through throughput, OEE, labour productivity, quality stability, unit cost, capital productivity and long-term reliability.

The second research question asked what role safety and operational data play as conditions governing progression. The answer is that safety and data function as governing conditions rather than secondary considerations. Safety acts as a gatekeeper: a higher level of substitution is permissible only if the target configuration can be deployed without unacceptable risk. Operational data act as an enabler: each level generates evidence that reduces uncertainty and supports informed decisions about whether and how to progress. Progression is therefore justified only when capability, safety, data and governance are aligned with enterprise performance objectives.

The theoretical contribution is threefold. First, the paper reframes robotisation from a system-capability problem into a work-substitution problem. Second, it connects robotic substitution with enterprise performance by linking each level to distinct performance mechanisms and indicators. Third, it integrates safety and operational data into the logic of progression, treating them as structural conditions of staged substitution rather than secondary implementation issues.

For managers, the framework provides a structured language for planning and evaluating robotisation. It helps distinguish between technological possibility and managerial desirability, and it legitimises intermediate and lower levels of substitution when they provide a better balance of productivity, flexibility, safety, cost and human capability. In this way, the framework helps engineering enterprises avoid both technological conservatism and automation determinism.

The study has limitations. The framework is conceptual and has not yet been empirically validated through case studies, quantitative analysis or longitudinal research. It does not provide universal quantitative thresholds for progression, because engineering tasks differ in risk, variability, volume, safety requirements and economic logic. The illustrative mapping is therefore not empirical validation, but a demonstration of how the framework can be applied to typical engineering operations. The paper also focuses on enterprise-level performance and does not fully address broader labour-market or societal consequences of robotisation.

Future research should validate the framework empirically. Comparative case studies could map existing robotic applications onto the six levels and examine whether managers recognise them as meaningful decision categories. Longitudinal studies could investigate how firms progress between levels and whether safety and data actually function as transition conditions. Quantitative research could measure how different substitution levels affect OEE, labour productivity, defect rates, ergonomic load, downtime, intervention frequency, value added per employee or capital productivity. Further work should also develop sector-specific adaptations for welding, assembly, internal logistics, machine loading, quality inspection and maintenance, and examine how firms can preserve tacit knowledge, prevent deskilling and build new capabilities as workers move from execution toward supervision, exception handling, maintenance, programming and governance.

The central conclusion is that robotisation should be understood as staged, performance-oriented and governed by safety and data. The value of robotic systems in engineering enterprises does not lie in autonomy for its own sake, but in their ability to transform specific units of work in ways that improve enterprise performance under acceptable safety, organisational and economic conditions.

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