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# AUTOMOTIVE INDUSTRY 4.0: PRECONDITIONS FOR THE ECONOMIC EFFECTIVENESS OF COLLABORATIVE AND MOBILE ROBOTICS

**Abstract**

Amid Kazakhstan's accelerated digitalization and national smart-manufacturing agenda, this paper presents a practice-oriented economic framework for evaluating, at the pre-design stage, the feasibility of deploying collaborative and mobile robotics in the automotive industry. The goal is to align engineering choices with production economics before on-site trials, reducing the risk of inflated expectations and showcase-only pilots. Methodologically, the framework combines conceptual modeling with quantitative screening: it decomposes total cost of ownership into capital and operating elements; maps operational effects across body/assembly stations, quality control, and in-plant logistics; and ties these effects to measurable KPIs – overall equipment effectiveness (and its Availability-Performance-Quality factors), cycle time, defect rates, planned/unplanned downtime, and safety incidents. A distinctive feature is the explicit integration of infrastructure constraints and risk factors – precision and calibration requirements, connectivity and communication quality, safety for human – robot collaboration, cybersecurity exposure, and workforce acceptance – into both the economics and a managerial go/no-go checklist. The framework yields (i) a reproducible pilot → expand → scale pathway with milestone metrics, (ii) a structured data package to enable subsequent statistical verification and learning across pilots, and (iii) adaptable accounting rules that fit local procurement and budgeting practices. By making trade-offs transparent and context-aware, the approach supports Kazakhstani automotive firms in selecting viable use cases, sizing investments, and sequencing deployments in line with national digitalization priorities.

**Keywords:** robotization, collaborative robots, mobile robots, automotive industry, overall equipment effectiveness, total cost of ownership, return on investment, Industry 4.0.

## Introduction

Amid global digitalization and rapid technological change, Kazakhstan's automotive industry faces the need to adapt to the challenges and opportunities associated with Industry 4.0. The transition to smart manufacturing based on the integration of cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and robotics opens new horizons for enhancing competitiveness, optimizing production processes, and reducing costs.

Within the Industry 4.0 context, particular attention is paid to collaborative and mobile robotics, which are becoming key elements of modern production lines. Collaborative robots (cobots) that operate in close interaction with humans provide flexibility and safety on the shop floor, while mobile robots enable the automation of intralogistics processes, which is especially relevant for large automotive plants.

According to the International Federation of Robotics (IFR), the global industrial robot market continued to expand in 2023, with more than 600,000 new installations projected by 2025 [1]. The automotive industry remains one of the main drivers of this growth and accounts for about 30 percent of all industrial robots. IFR forecasts also indicate that the global stock of collaborative robots will increase by about 40 percent by 2025, reflecting growing interest in this technology. The IFR 2023 report further notes rising adoption of cobots by small and medium-sized enterprises, which is pertinent for Kazakhstan where such firms play a significant role in the economy.

For Kazakhstan, where the automotive sector is strategically important, the deployment of these technologies can become a decisive step toward technological modernization and higher economic efficiency. Successful implementation, however, requires not only investment in equipment and infrastructure but also the preparation of qualified personnel capable of working with new technologies.

In recent years, Industry 4.0 and robotics have been extensively examined in the scholarly literature. Studies by Lu and Xu et al. [2–3] underscore the importance of digital transformation for strengthening the competitiveness of industrial firms. Lu, in “Industry 4.0: A survey on technologies, applications and open research issues,” identifies the core technologies of Industry 4.0-such as the Internet of Things (IoT), artificial intelligence (AI), and robotics-and analyzes their effects on production processes. Xu et al., in “Industry 4.0: State of the art and future trends,” emphasize the role of cyber-physical systems (CPS) in enabling flexible and adaptive production lines.

Research by Wang et al. and Lee et al. [4–5] highlights how CPS and smart factories underpin flexible, adaptive manufacturing. Wang et al., in “Current status and advancement of cyber-physical systems in manufacturing,” propose a CPS architecture suitable for integrating robotics into automotive production with a high degree of automation and control. Lee et al., in “A cyber-physical systems architecture for Industry 4.0-based manufacturing systems,” stress the importance of integrating IoT and AI into production workflows.

Within collaborative robotics, Ionescu and Negulescu and Krüger et al. [6–7] demonstrate how human-robot interaction can improve both productivity and safety. Ionescu and Negulescu, in “Collaborative robots in automotive industry: A review,” argue that collaborative robots are particularly effective in tasks requiring high precision and repeatability, making them well suited to automotive manufacturing. Krüger et al., in “Cooperation of human and machines in assembly lines,” show how cobots can enhance human-machine cooperation on the shop floor.

Regarding mobile robotics, Bogue and Khamis et al. [8–9] examine how mobile platforms optimize intralogistics, reducing downtime and raising overall efficiency. Bogue, in “Growth in e-commerce boosts the market for mobile robots in warehouses,” notes that surging e-commerce demand has accelerated adoption of mobile robots - a trend that is relevant to automotive plants where logistics is a critical lever. Khamis et al., in “Mobile robot navigation and collision avoidance in dynamic environments,” investigate navigation, perception, and collision-avoidance capabilities under complex production conditions.

The objective of this article is to examine the preconditions for the economic effectiveness of collaborative and mobile robotics in Kazakhstan’s automotive industry and to identify the key barriers and opportunities for their adoption. The analysis covers global trends, international experience, and the specific features of the Kazakhstani market in order to formulate recommendations for further sectoral development under ongoing digital transformation.

**Materials and methods**

This article draws on international research on the adoption of collaborative robots (cobots) and on the economics of their deployment, on the literature measuring manufacturing performance through Overall Equipment Effectiveness (OEE) and related indicators, and on studies of how robotization affects productivity, labor investment, and organizational outcomes.

At the techno-economic assessment (TEA) stage, prior to field data collection, we employ a "conceptual-quantitative" approach that comprises: (a) decomposition of Total Cost of Ownership (TCO) into capital expenditures (CAPEX: equipment, systems integration, infrastructure, training) and operating expenditures (OPEX: technical maintenance, software, calibrations, commissioning and stabilization downtime, energy, workforce upskilling); (b) mapping of operational effects by process area (assembly, quality inspection, in-plant logistics); (c) alignment with Key Performance Indicators (KPI), with Overall Equipment Effectiveness (OEE) defined as OEE = A × P × Q, where A denotes equipment availability, P performance, and Q quality; (d) a managerial go/no-go checklist for implementation conditions that includes information-technology and operational-technology integration (IT/OT), safety of human-robot collaboration (HRC), a workforce training program, and a Service Level Agreement (SLA).

**Results**

Technological and organizational prerequisites for the effect

The deployment of collaborative robots (cobots) and mobile platforms in automotive manufacturing creates new opportunities to increase flexibility, repeatability, and overall process efficiency. The success of such initiatives, however, depends on a set of technological and organizational factors that must be addressed at both the planning and execution stages.

Collaborative robots differ from traditional industrial robots through their ability to work in close proximity to humans, which makes them well suited to tasks that require flexibility and adaptability. Cobots can execute tasks with high repeatability, reducing human-factor errors and improving product quality. In automotive settings, for example, cobots can be applied to small-parts assembly, painting, or quality inspection where accuracy and repeatability are critical [10, 11].

Key success factors for cobots include careful task selection, since not every operation is appropriate for cobot automation. Priority should be given to tasks that demand high precision and repeatability yet do not require complex dexterous manipulation that traditional robots might handle better. Another factor is the design of human–robot collaboration zones (HRC), which must ensure both safety and throughput, including the configuration of speed profiles, safety boundaries, and visual and acoustic alerts. A third factor is the standardization of work. To realize the full benefit of cobot deployment, operations should be standardized to minimize variability and to stabilize execution [12].

Mobile robots play a central role in optimizing intralogistics. They automate the transport of materials, parts, and finished goods between production areas, which reduces waiting and movement losses. This is particularly important at large automotive plants where logistics flows are complex and multi-layered.

The advantages of mobile platforms include continuous, around-the-clock operation that shortens transport times and minimizes idle periods. Logistics automation helps level the production flow, which is critical in processes where bottlenecks can trigger delays. Mobile robots also reduce work-in-process inventory, with a positive impact on overall manufacturing efficiency [4, 7].

The effectiveness of both cobots and mobile platforms depends strongly on data quality and on integration with other production-control systems. Stable telemetry, batch-level traceability, and synchronization with a Manufacturing Execution System (MES) and an Enterprise Resource Planning (ERP) system are necessary conditions for realizing maximum benefits. Data streamed from robots must be accurate and timely to support effective process control, and end-to-end tracking of each batch of materials and parts across all stages helps minimize errors and improve quality. Seamless integration with MES and ERP enables automated planning, control, and reporting, which raises overall production efficiency [8, 9].

Successful adoption is not possible without workforce engagement. A clear role model and a structured training plan are required to unlock the full effect, encompassing operator instruction on new equipment and the involvement of engineers and managers throughout deployment. Without staff buy-in, projects risk resistance, underutilization of equipment, and diminished efficiency [5, 13].

The maturity of a firm's robotization practices is a critical success factor. Evidence from samples of Italian manufacturing enterprises indicates that higher robotization maturity is associated with deeper integration of processes and competencies. This encompasses not only technical facets but also organizational change, including the introduction of standard work and systematic workforce training. A key aspect is end-to-end process integration, whereby all robot-related activities are embedded within the overarching production-management system. Such integration helps prevent supply-chain discontinuities and raises overall efficiency. Equally important is workforce readiness for new technologies, which requires continuous learning and skills development.

Robot deployment frequently necessitates adjustments to organizational structure and managerial processes, and these shifts should be anticipated and budgeted at the planning stage [14].

Infrastructure limitations and risks

The deployment of collaborative robots and mobile platforms in the automotive industry entails a set of infrastructure constraints and risks that can materially affect both economic viability and project success. These constraints are technical and organizational in nature, and neglecting them may lead to cost overruns, productivity losses, and schedule slippage. A review of recent literature, including Silva et al. (2024), Polonara et al. (2024), and Țîțu et al. (2024) [10–12], indicates that the principal infrastructure risks comprise precision and calibration of equipment, connectivity and communication quality, workspace organization and safety, cybersecurity and software updates, and workforce acceptance of new technologies. Each factor warrants careful analysis and explicit planning during both the design and implementation phases.

One of the infrastructure constraints and risks concerns precision and calibration of equipment. Effective operation of collaborative and mobile robots depends on high-accuracy sensors, cameras, and fiducials together with timely calibration of all measurement and actuation subsystems. Even small deviations propagate into execution errors, higher defect rates, and increased operating costs. Calibration and metrological control should therefore be budgeted within operating expenditures, including allowance for the downtime required to perform these procedures [4, 10].

Another constraint and risk relates to connectivity and communication quality. Reliable data exchange among robots, peripheral devices, and supervisory control systems requires an industrial network with predictable latency and stable radio coverage. The use of industrial wireless, fifth-generation cellular networks, and industrial Ethernet becomes a necessary condition, since electromagnetic interference, shielding structures, and long distances degrade quality of service and can cause task delays and a decline in overall manufacturing efficiency [11, 12].

Another significant infrastructure constraint and risk concerns workspace design and safety. The width of aisles, the configuration of work zones, and the correct setting of speed profiles for mobile platforms directly determine route capacity and actual takt time. Technical and organizational safety measures such as visual and acoustic alerts, zone marking, slow-down and stop scenarios, and codified rules for human–robot co-working reduce the risk of collisions and injuries and prevent bottlenecks and unplanned delays [7, 10].

Cybersecurity and software updates also constitute important constraints and risks. Growing digital connectivity increases exposure to unauthorized access, which calls for a hardened architecture, formal vulnerability-management procedures, and planned maintenance windows for updates with pre-deployment testing and rollback options. Even beneficial patches can cause unplanned downtime, so update cycles must be coordinated with production schedules to preserve operational stability and the expected economic benefits [8, 9].

Finally, workforce acceptance of new technologies and adherence to occupational health and safety regimes is a decisive constraint and risk. The economic return depends on staff engagement, a structured training program, clear role delineation, and consistent managerial support. In the absence of these conditions, equipment underutilization and organizational drift are likely. Systematic briefings, drills, and compliance monitoring for safe human-robot collaboration help sustain the effect and prevent incidents [5, 13].

Methodological framework for economic evaluation (TCO/ROI)

To evaluate the economic effectiveness of deploying collaborative and mobile robots in the automotive industry, we adopt a methodological framework based on Total Cost of Ownership (TCO) and Return on Investment (ROI). The framework accounts for both capital expenditures (CAPEX) and operating expenditures (OPEX) and links them to production Key Performance Indicators (KPI).

Total Cost of Ownership is the overall cost of owning and operating equipment over its life cycle, encompassing both capital and operating outlays. On the CAPEX side, the analysis includes a cobot or manipulator with peripheral equipment such as end-of-arm tooling, cameras, and sensors; a mobile platform with navigation systems and sensors; guarding, scanners, and other safety devices; systems integration and commissioning; information- and operational-technology infrastructure including networks, servers, and software; and training for operators and engineers. On the OPEX side, the analysis includes scheduled and unscheduled maintenance; software licenses and updates; regular calibrations and metrological control; consumables and replacement of wear parts; energy consumption; commissioning and stabilization downtime; and additional workforce training [14, 15].

The deployment of collaborative and mobile robots generates both direct and indirect benefits across production stages. Direct benefits include improved assembly and inspection due to higher repeatability and lower defect rates, which contributes to the quality component Q, and faster in-plant logistics through reduced transport and waiting times, which raises equipment availability A and task performance P. Indirect benefits include enhanced workplace safety and ergonomics, lower injury rates, and higher employee retention, all of which have a positive effect on overall manufacturing efficiency [16, 17].

Key Performance Indicators are used to evaluate the effectiveness of robotization, with Overall Equipment Effectiveness (OEE) taking a central role and defined as the product of availability (A), performance (P), and quality (Q), that is, $OEE = A \times P \times Q$. The accounting rules include establishing a baseline from average per-shift indicators over no fewer than four weeks prior to deployment, excluding extreme shifts and anomalous events, setting a stabilization window to capture the transition to steady-state operation, logging all equipment events and synchronizing telemetry with Manufacturing Execution Systems (MES), and conducting sensitivity analysis with respect to the discount rate in the range of 8–15 percent, equipment utilization, the workforce learning curve, and the share of unplanned downtime [18, 19].

Before implementation begins, several conditions must be confirmed. Information-technology and operational-technology integration has been completed, and data exchange has been tested. Human-robot collaboration zones comply with safety requirements. The route network for mobile platforms has been designed and throughput tested. Training cards and a workforce training plan have been developed and approved. Service Level Agreements are in place for service and metrology. The KPI set is measurable, technically implementable, and agreed with management [20, 21].

For successful adoption, a pilot project of eight to twelve weeks is recommended. Week 0 covers baseline diagnostics and equipment preparation. Weeks 1–3 cover tuning and testing. Weeks 4–8 cover steady-state operation and data collection. The effect is assessed by comparing pre- and post-deployment indicators. Where a comparable control area is available, a difference-in-differences approach can be applied, and external validity is supported through benchmarking against industry data [22, 23].

Thus, the TCO and ROI-based evaluation framework structures costs, operational effects, and the conditions for a managed pilot, linking engineering choices to manufacturing performance metrics.

**Discussion**

Modern research confirms the economic potential of collaborative and mobile robotics, but emphasizes the dependence of results on organizational maturity, data quality, and the proper design of experiments. The effect is heterogeneous across operation types and contexts: in some cases, productivity and quality gains are achieved without increasing employment, while in others, roles and competencies are redistributed. The actual return is determined by the company's ability to maintain a stable cycle time, manage variability and data discipline (MES/ERP/SCADA), and adhere to OEE and related KPI accounting rules.

In the Kazakh context, the window of opportunity is expanding due to the political and institutional agenda of digital transformation [24]: the declared course toward a "fully digital nation" in 2025–2027, the development of a "Digital Code," the formation of a unified Digital Qazaqstan strategy, and the creation of a specialized body for artificial intelligence and digital development set the framework conditions – rules, institutions, priorities, and pilot sites (including the Alatau City project). This architecture reduces transaction costs for enterprises, simplifies access to supporting infrastructure (data, connectivity, computing power), and increases the predictability of return on investment. However, the presence of "rules of the game" is no substitute for operational readiness: cobots and mobile platforms only deliver sustainable results with standardized operations, qualified personnel, and managed IT/OT integration.

The country's current robotics footprint is still limited. According to estimates, there are fewer than 5 industrial robots per 10,000 workers (around a hundred devices for several dozen enterprises), significantly below the level of leading countries. This is due to relatively small serial production volumes, fragmented automation, a shortage of personnel for operation and maintenance, and insufficient data and process preparation for a sustainable cycle. For the automotive industry, this means that an economically viable start is not with "continuous" automation, but with targeted tasks with high repeatability, a risk profile, and measurable returns: "heavy" and monotonous assembly and quality control operations (contributing to Q and P), intra-production logistics in bottlenecks (contributing to A and P), and ergonomic risk nodes (reducing injuries and indirect costs).

Sectoral cases in related industries (rail logistics, marshalling hubs, healthcare, mining, and energy) demonstrate that with data discipline and well-thought-out integration, digital solutions are scalable and deliver economic benefits. For automakers, this translates into a prioritized "digital loop": equipment telemetry, batch and component traceability, end-to-end product identifiers, a library of standard operations, shift and changeover procedures. It is the "data loop" that transforms a cobot from a standalone device into a production tool for variability management, and a mobile platform into a resource for flow alignment.

The key constraints on scaling are infrastructure risks and organizational readiness: accuracy and calibration (regular metrology as an element of OPEX), connectivity and connection quality (predictable latencies, stable coverage), layout and security (aisle widths, speed profiles, HRC modes), cybersecurity and update management (patch management with "windows," testing, and rollbacks), as well as staff acceptance and HSE compliance. In practice, this means that the "project economics" must include a risk reserve (10–15% CAPEX/OPEX) and a managed stabilization plan (at least 4–8 weeks after launch), and the target model must include a training and certification program for personnel (operators, setup technicians, metrology engineers, information security specialists).

National institutions and partnerships act as ecosystem elements accelerating implementation: technology parks and accelerators (Astana Hub), research and education centers and workshops (including international ones), specialized training programs (Tech Orda, Industrial PhD), international cooperation (China, Germany, France, USA), and emerging robotics competence centers. In the automotive industry, it would be appropriate to establish an industry-specific Competence Center based at leading production sites and corporate universities. This would consolidate standard process routes, a library of HRC tooling and scenarios, calibration and metrology methods, as well as TCO/ROI calculation templates and data packages for statistical validation.

Finally, the specific nature of the Kazakhstani market - a significant share of small- and medium-volume products – dictates specific design requirements: modular cobot cells with quick changeovers, lightweight visual inspection, and mobile transport and logistics scenarios based on a fleet of autonomous platforms compatible with existing infrastructure. This fits into the logical sequence "pilot → expand → scale": pilots in high-risk areas with controlled variability, subsequent expansion to related operations, and scaling to product families where OEE, quality, and safety benefits have been proven.

## Conclusion

This paper develops a replicable economic framework for the preliminary assessment of collaborative and mobile robotics implementation in the Kazakhstan automotive industry. The framework includes a total cost of ownership structure, an operational benefit map, rules for accounting for and validating impacts, and a list of go-no-go conditions. The data-driven approach links engineering decisions with operational performance metrics, reducing the risk of showcase pilots and making management decisions more predictable.

Considering national digital transformation priorities, a practical roadmap for automotive companies consists of three stages.

1) Quick wins. Six to twelve-month horizon. Cobot cells for highly repeatable operations with significant ergonomic risks. Visual quality control for critical tolerances. Autonomous intra-plant

logistics on narrow routes. KPI targets include an increase in overall equipment efficiency by five to eight percentage points, a reduction in defects by twenty to thirty percent for critical items, and a reduction in cycle time by ten to fifteen percent for selected operations.

2) Scaling. Time horizon: twelve to twenty-four months. Transferring proven templates to related operations and product families. Consolidating data loops across MES, ERP, and SCADA systems. Implementing predictive maintenance for bottleneck nodes. Unifying human-robot interaction modes and metrology procedures.

3) Institutionalization. Timeframe: 24 months or more. Establishment of an industry-specific center of excellence based on leading platforms and corporate universities. Localization of service competencies and some components. Joint projects with universities in the Industrial PhD format. Combination of funding sources and application of tax incentives for robotics.

Critical prerequisites for success include data and measurement discipline, managed integration of information and operational technologies, targeted personnel training, and a well-developed risk framework for calibration, connectivity, cybersecurity, and occupational health and safety requirements. When these conditions are met, the total cost of ownership and return on investment methodology and the step-by-step logic of the pilot expand scale create a realistic path for Kazakhstani automotive companies to increase sustainability, productivity, and quality, and at the industry level, to strengthen technological sovereignty, increase highly skilled employment, and grow added value.

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# АВТОКӨЛІК ӨНДІРІСІНДЕГІ ИНДУСТРИЯ 4.0: КОЛЛАБОРАТИВТІ ЖӘНЕ МОБИЛЬДІ РОБОТОТЕХНИКАНЫҢ ЭКОНОМИКАЛЫҚ ТИІМДІЛІГІНІҢ АЛҒЫШАРТТАРЫ

**Аңдатпа**

Қазақстанның жедел цифрлануы мен ұлттық smart-өндіріс күн тәртібі аясында бұл мақала автокөлік өнеркәсібінде коллаборативті және мобильді роботтарды енгізудің жобалау алдындағы кезеңінде жүзеге асырылатын, тәжірибеге бағытталған экономикалық бағалау шеңберін ұсынады. Мақсат – инженерлік шешімдерді өндірістік экономикамен алдын ала үйлестіру арқылы орынсыз күтілімдер мен «витриналық» пилоттардың тәуекелін азайту. Әдістемелік тұрғыдан шеңбер концептуалды-сандық тәсілді қолданады: иегерліктің толық құнын (TCO) капиталдық және операциялық құрамдастарға бөледі; дене/жинақтау станциялары, сапаны бақылау және цехішілік логистика бойынша операциялық әсерлерді картаға түсіреді; оларды KPI-лармен байланыстырады-жабдықтың жалпы тиімділігі (OEE) және оның A-P-Q құрамдары, цикл уақыты, ақаулар үлесі, жоспарлы/жоспардан тыс тоқтап қалу, қауіпсіздік оқиғалары. Ерекшелігі – инфрақұрылымдық шектеулер мен тәуекелдерді (дәлдік пен калибрлеу, байланыс/коммуникация сапасы, адам-робот өзара әрекеттесуіндегі қауіпсіздік, киберқауіпсіздік, кадрлардың қабылдауы) экономикалық есепке тікелей енгізу және басқарушылық go/no-go чек-тізіміне көшіру. Нәтиже ретінде (i) көрсеткіштік межелермен «пилот → кеңейту → масштабтау» траекториясы, (ii) кейінгі статистикалық верификацияға арналған құрылымдалған деректер пакеті және (iii) жергілікті сатып алу мен бюджеттеу тәжірибелеріне бейімделетін есептік қағидалар қалыптастырылады. Ұсынылған тәсіл қазақстандық автокөлік кәсіпорындарына жарамды қолдану кейстерін таңдап, инвестиция көлемін дәл бағалауға және ұлттық цифрландыру басымдықтарына сай енгізу ретін жоспарлауға мүмкіндік береді.

**Тірек сөздер:** роботтандыру, коллаборативті роботтар, мобильді роботтар, автокөлік өнеркәсібі, жабдықтың жалпы тиімділігі, иеленудің толық құны, инвестициялардың қайтарымдылығы, индустрия 4.0.

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# ИНДУСТРИЯ 4.0 В АВТОПРОМЕ: ПРЕДПОСЫЛКИ ЭКОНОМИЧЕСКОЙ ЭФФЕКТИВНОСТИ КОЛЛАБОРАТИВНОЙ И МОБИЛЬНОЙ РОБОТОТЕХНИКИ

**Аннотация**

На фоне ускоренной цифровой трансформации Казахстана и национальной повестки смарт-производства статья предлагает практико-ориентированную экономическую рамку для предпроектной оценки целесообразности внедрения коллаборативных и мобильных роботов в автомобилестроении. Цель – заранее выровнять инженерные решения с производственной экономикой, снизив риск завышенных ожиданий и «витринных» пилотов. Методологически применяется концептуально-количественный подход: полная стоимость владения (TCO) декомпозируется на капитальные и операционные элементы; операционные эффекты в зонах сборки, контроля качества и внутризаводской логистики картируются и связываются с KPI – общей эффективностью оборудования (OEE) и ее составляющими A-P-Q, временем цикла, уровнем дефектов, плановыми/внеплановыми простоями и показателями безопасности. Ключевое отличие – явная интеграция инфраструктурных ограничений и рисков (точность и калибровка, качество связи и коммуникаций, требования безопасности HRC, кибербезопасность, принятие со стороны персонала) как в экономические расчеты, так и в управленческий чек-лист go/no-go. Результатом выступают: (i) воспроизводимая логика «пилот → расширение →

масштаб», привязанная к контрольным метрикам; (ii) структурированный пакет данных для последующей статистической верификации и обучения между пилотами; (iii) адаптируемые правила учета, совместимые с местными практиками закупок и бюджетирования. Подход делает компромиссы прозрачными и контекстно чувствительными, помогая казахстанским автопредприятиям выбирать жизнеспособные кейсы, оценивать инвестиции и планировать поэтапное внедрение в русле национальных приоритетов цифровизации.

**Ключевые слова:** роботизация, коллаборативные роботы, мобильные роботы, автомобильная промышленность, общая эффективность оборудования, общая стоимость владения, окупаемость инвестиций, индустрия 4.0.

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