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PRACTICAL IMPLEMENTATION OF ASSEMBLY LINE AUTOMATION AT A MACHINE-BUILDING ENTERPRISE AND ITS ECONOMIC ASSESSMENT

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In the modern era of advanced technologies, industries worldwide strive to improve their production efficiency through automation. Automation plays a key role in industrial development by optimizing processes and reducing human involvement. In Kazakhstan, mechanical engineering is one of the priority sectors, yet many enterprises still face challenges in fully realizing their production potential due to limited automation. The study focuses on the automation of lifting mechanisms on the assembly line of SaryarkaAvtoProm LLP. The aim is to develop a programmable logic controller (PLC)-based system that increases production safety, reduces risks, and improves efficiency. The proposed approach provides a solution not only for the chosen enterprise but also for other machine-building industries with similar assembly processes.

Key words: *production digitalization; control system; assembly line; labor safety; innovative technologies; industrial automation; production process.*

МАШИНА ЖАСАУ КӘСІПОРНЫНДА ҚҰРАСТЫРУ ЖЕЛІСІН АВТОМАТТАНДЫРУДЫ ПРАКТИКАЛЫҚ ТҰРҒЫДАН ІСКЕ АСЫРУ ЖӘНЕ ОНЫҢ ЭКОНОМИКАЛЫҚ БАҒАЛАНУЫ

Наурзбаева К.Б. – «СарыаркаАвтоПром» ЖШС «Аллюр» зауытының жаңа жобаларды іске қосу тобының жетекшісі, Қостанай қ., Қазақстан Республикасы.*

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Қазіргі заманда озық технологиялардың дамуына байланысты кәсіпорындар өндірістің тиімділігін арттыру үшін автоматтандыруға ұмтылуда. Автоматтандыру өндірістік процестерді оңтайландырып, адам қатысуын азайту арқылы өнеркәсіптің дамуына ықпал ететін негізгі фактор болып табылады. Қазақстанда машина жасау саласы басым бағыттардың бірі болғанымен, көптеген кәсіпорындар автоматтандырудың жеткіліксіз деңгейіне байланысты өз өндірістік әлеуетін толық жүзеге асыра алмай отыр. Бұл зерттеуде «СарыаркаАвтоПром» ЖШС-нің құрастыру желісіндегі жүккөтергіш механизмдерді автоматтандыру қарастырылады. Зерттеудің мақсаты – өндірістің қауіпсіздігін арттыратын, тәуекелдерді азайтатын және өнімділікті жоғарылататын бағдарламаланатын логикалық контроллерге (ПЛК) негізделген басқару жүйесін әзірлеу. Ұсынылған тәсіл тек зерттелген кәсіпорынға ғана емес, сондай-ақ ұқсас өндірістік процестері бар басқа да машина жасау салаларына қолданылуы мүмкін.

Түйінді сөздер: *өндірісті цифрландыру; басқару жүйесі; жинақтау желісі; еңбектің қауіпсіздігі; инновациялық технологиялар; өнеркәсіптік автоматтандыру; өндірістік процесс*

ПРАКТИЧЕСКОЕ ВНЕДРЕНИЕ АВТОМАТИЗАЦИИ СБОРОЧНОЙ ЛИНИИ НА МАШИНОСТРОИТЕЛЬНОМ ПРЕДПРИЯТИИ И ЕЕ ЭКОНОМИЧЕСКАЯ ОЦЕНКА

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В современную эпоху развития передовых технологий предприятия стремятся к повышению эффективности производства за счет автоматизации. Автоматизация является ключевым фактором развития промышленности, позволяя оптимизировать процессы и сократить участие человека. В Казахстане машиностроительная отрасль является приоритетной, однако многие предприятия сталкиваются с трудностями в реализации своего производственного потенциала из-за недостаточного уровня автоматизации. В данной работе рассматривается автоматизация грузоподъёмных механизмов на сборочной линии ТОО «СарыаркаАвтоПром». Цель исследования – разработка системы управления на базе программируемого логического контроллера (ПЛК), обеспечивающей повышение безопасности, снижение рисков и рост производительности. Предложенный подход может быть применен не только на выбранном предприятии, но и в других машиностроительных производствах со схожими процессами.

Ключевые слова: *цифровизация производства; система управления; сборочная линия; безопасность труда; инновационные технологии; промышленная автоматизация; производственный процесс.*

Introduction. In the context of the emergence of Industry 4.0, based on the integration of cyber-physical systems, the Industrial Internet of Things (IoT), and big data technologies, the integrated automation of production processes is emerging as a strategic vector for increasing the competitiveness of the industrial sector. Automation is viewed as a system-forming driver of industrial development, enabling the end-to-end digitalization of process chains, intelligent resource management, and the transition to flexible production models.

Key tools for this transformation include distributed supervisory control and data acquisition (SCADA) systems, programmable logic controllers (PLCs), and integrated platforms for real-time data analysis, enabling predictive maintenance and optimization of production flows. Together, these solutions create a cyber-physical production environment where design, monitoring, and management processes operate in a self-regulating and highly fault-tolerant manner [1].

In the Republic of Kazakhstan, the institutional framework for the accelerated implementation of these technologies is provided by the State Industrialization Program, aimed at creating digital production ecosystems. According to the Bureau of National Statistics of the Agency for Strategic Planning and Reforms, in 2022 the total volume of mechanical engineering production reached 1,085.6 billion tenge, which in nominal terms is 35% higher than the figure for the same period in 2021 [2].

Mechanical engineering is a systemically important and priority sector of the manufacturing industry in the Republic of Kazakhstan, possessing significant potential for expanding production capacity, exporting high-tech products, and integrating into global value chains [3]. Its development vector is aligned with the objectives of shaping the fourth industrial revolution (Industry 4.0), where digitalization and comprehensive automation are key factors of competitiveness.

At the state policy level, this priority has been confirmed at the highest level: according to a statement by the President of the Republic of Kazakhstan, Kassym-Jomart Tokayev, by 2025, it is planned to fully automate approximately 200 industrial enterprises, making the implementation of cyber-physical production systems and the Industrial Internet of Things (Industrial IoT) an integral stage of the structural modernization of the national economy [4]. The implementation of this strategic direction is supported by government incentives, including expanded partnerships with international technology leaders. A typical example is the institutionalized cooperation of the Government of the Republic of Kazakhstan, represented by the Prime Minister, with the American company Honeywell, which specializes in the production of integrated solutions in the field of industrial automation systems, control and predictive analytics [5].

The historical context of automation development in mechanical engineering illustrates the evolution from electromechanical relay devices with magnetic coils and short-circuit contacts, which, prior to the widespread adoption of digital technologies, performed logical control functions in various industries. However, the operational limitations of such systems–large dimensions, limited service life of switching elements, and the need for high-cost maintenance–led to increased costs and significant demands on personnel qualifications. Diagnosing faults involving hundreds or thousands of relays required the deployment of multilayer monitoring systems and the involvement of a significant number of specialists [6].

The transition to programmable logic architectures resulted in a technological leap: solutions were developed that integrated the functions of thousands of relays, timers, and counters into compact, multifunctional modules with programmable logic controllers (PLCs) supporting IEC 61131 standards and providing flexible reconfiguration of production lines [7]. The IEC 61131 standard regulates programming languages and PLC architecture, ensuring the interoperability and scalability of control systems internationally. Combined with MES (Manufacturing Execution Systems) and SCADA (Supervisory Control and Data Acquisition) practices compliant with IEC 62264 and ISO 22400, these solutions enable the formalization of key performance indicators (KPIs), support end-to-end data exchange between planning and production levels, and implement predictive equipment maintenance.

The SaryarkaAvtoProm automobile assembly plant, part of the Allur industrial group, was chosen as a pilot site for testing these technologies. According to the company's official data, SaryarkaAvtoProm is the largest automobile manufacturer in the Republic of Kazakhstan and the first enterprise certified in accordance with full-cycle industrial assembly requirements, including welding, painting, and final body assembly. The plant has production capacities that are unique for the country, allowing it to produce a wide range of vehicles, which makes it a representative object for research in the field of industrial automation and the implementation of smart manufacturing technologies [8].

Despite the state industrial policy being implemented and the observed positive development dynamics, some mechanical engineering enterprises in the Republic of Kazakhstan are not fully realizing their production potential due to technological and infrastructural limitations. Entering new market segments and increasing production volumes requires a comprehensive set of measures to improve production processes and implement a deep digital transformation, including the automation of key assembly lines. However, full-scale automation requires a comprehensive reconstruction of existing production facilities, which entails significant capital expenditures, risks of temporary production downtime, and the need for careful modernization planning.

In response to these challenges, modern innovative solutions based on the use of programmable logic controllers (PLCs), specialized electronic computers for automating technological processes, are becoming increasingly important. Programmable logic controllers (PLCs) provide a high degree of reliability, flexible reconfiguration, and the ability to integrate with higher-level systems such as SCADA and MES, compliant with international standards IEC 61131 and IEC 62264. Implementation of such solutions enables the gradual automation of individual production areas without completely dismantling existing lines, minimizing downtime and reducing the financial risks of capital projects.

Despite the company's use of advanced technologies, an analysis of the current state of its production infrastructure reveals areas with insufficient automation, which reduces overall production efficiency. A prime example of partially automated equipment is the lifting mechanism (LM) used on the assembly line to handle car bodies. This mechanism performs key process operations: vertical movement (raising and lowering) of the body at work stations and its transportation between stages of the assembly process. In the context of the technological revolution and Industry 4.0, the use of lifting and transport systems (truck cranes, manipulators, specialized lifts) is becoming an integral element of the modern industrial complex. These devices provide not only mechanization but also deep automation of primary and auxiliary technological operations, which helps reduce labor intensity, improve safety, and increase productivity [9].

The scientific novelty of this study lies in the development and verification of an automated control system for lifting mechanisms that previously operated exclusively mechanically and lacked digital automation. This study implements automation from scratch, transforming traditionally mechanical equipment into a cyber-physical control system.

It should be emphasized that in industrial practice, lifting mechanisms are conventionally divided into two classes:

- initially automated systems, which are designed and manufactured with integrated digital control systems;
- purely mechanical devices, the operation of which requires direct human intervention and is not designed for automation.

The latter class is characterized by functional and operational limitations—high labor intensity, increased risk of failure, and limited productivity. This study aims to overcome these limitations by creating a comprehensive automation architecture. The objective of the study is to develop a unified, easily scalable automated control system and associated algorithmic support for implementation on the assembly line of Kazakhstan's largest automaker, SaryarkaAvtoProm LLP (Allur Group of Companies, Kostanay Region). The study involves the creation and integration of new digital technologies that enable the automation of production processes and the subsequent commercialization of the results in related industries. SaryarkaAvtoProm, in this context, serves as an experimental platform for the development and testing of a prototype, the subsequent industrial replication of which is not limited to the mechanical engineering sector.

Particular attention is paid to the creation of software for a highly versatile assembly and automation system, which will enable the developed solution to be used in any production environment, including areas with overhead transport systems such as LM (Lifting Mechanism). Research Stages and Methodology

To achieve this goal, the following key stages were identified:

1. Structural and functional analysis of the assembly line lifting and loading mechanism, including a detailed study of the process operations to be automated and identification of critical points in the production process.

2. Design and preliminary modeling of the automated system structure, including calculation of power characteristics and selection of actuators and sensor components.

3. Graphical development of automatic control circuits and algorithms, including the construction of block diagrams for the interaction of hardware and software modules.

4. Development of control software based on a programmable logic controller (PLC) using IEC 61131 standards, ensuring interoperability and scalability of the solutions.

5. Validation and pilot implementation of the prototype on the assembly line, including testing on real equipment, subsequent optimization of the algorithms, and preparation for commercialization of the results.

Materials and Methods. This study provides a scientific and practical basis for transforming traditional mechanical lifting systems into intelligent automated systems, paving the way for the replication of these solutions in various industries—from mechanical engineering to logistics and warehousing.

The subject of the experimental work is a "Lifting Mechanism" (LM), operated on an automotive assembly line and designed to move car bodies between processing stations. Structurally, the LM is a system comprising two asynchronous electric motors with a total installed power of approximately 1.5 kW, a winch system, and a carriage with a gripper-holding unit that enables the transport of the car body. The nominal weight of the transported load reaches 2 tons, which, when operated manually, creates significant risks of industrial injuries and accidents due to human error and the likelihood of operator error.

In the current configuration, the LM is controlled by the operator in a fully mechanized mode, without automatic control or active protection. The body is moved linearly along the overhead crane, requiring constant personnel presence and a high probability of abnormal loads. Of the seven operating assembly lines at the plant, only two are fully automated, confirming the systemic need for digitalization of key production operations.

To eliminate the identified risks and improve production reliability, the study proposes the implementation of a programmable logic controller (PLC) as the basic element of the automated control system. A PLC combines the functions of relay logic, timers, and counters in a compact module, ensuring:

- high-speed computing and reliability under industrial conditions;
- flexibility of scaling and reconfiguration without complete hardware replacement;
- support for IEC 61131 standards, ensuring interoperability with higher-level SCADA and MES systems.

A key area of research is the transition from traditional programming to a "parametric approach," which will enable the development of automatic control algorithms through adaptive configuration rather than the creation of individual program codes for each node. To this end, specialized software will be developed focused on:

1. Optimizing the interface between the operator and the PLC system to minimize input errors and speed up development;

2. Creating universal control algorithms applicable to various types of material handling equipment without the need for extensive code modification;

3. Ensuring fault tolerance and preventing emergency situations when moving loads weighing up to 2 tons through the implementation of position sensor systems, speed limiting, and overload monitoring.

The integration of the PLC and the developed software will:

- improve industrial safety by eliminating critical operator errors;
- reduce the development and commissioning time of an automated system compared to expensive robotic systems;
- ensure modularity and replicability of solutions across various industrial production areas, not limited to automotive assembly.

This approach develops a scientifically based methodology for the phased digitalization of lifting and handling operations, laying the foundation for the subsequent implementation of intelligent cyber-physical systems in automotive manufacturing production chains.

The lifting and handling equipment under study is a system comprising two asynchronous electric motors with a total installed power of approximately 1.5 kW, a hoist system, and a carriage (trolley) for gripping and holding the vehicle body. In the existing assembly process, the lifting mechanism (LM) is controlled manually: the operator independently sets the direction and timing of the body movement. This operating method is characterized by a higher level of production risk, as key operations are directly dependent on human error.

The LM's working load reaches approximately 2 tons, which, when controlled manually, significantly increases the likelihood of accidents: any imprecise movement or uncoordinated action can result in damage to the product being moved, process equipment, or harm to the life and health of personnel. Therefore, the current operation of the mechanism is considered inherently unreliable in the context of modern industrial safety requirements.

This type of lifting mechanism has not previously been subject to comprehensive automation, which distinguishes it from similar devices operating on fully automated assembly lines. The latter are designed with control systems and electrical components integrated into the design process, eliminating the need for constant operator intervention and allowing for the full implementation of automatic control systems. In contrast, the LM under study was designed as a mechanized, not automated, machine, which complicates subsequent digitalization and requires adaptive solutions for integrating industrial automation elements.

With the development of industry and the economy, electrical automation has become a fundamental technological tool in a variety of industries, from construction to high-tech aerospace. According to several studies [10], electromechanical and electroautomatic systems demonstrate the greatest efficiency in heavy industry and the energy sector, ensuring high productivity and reducing operational risks.

Modern trends indicate significant potential for improving the efficiency of electrical automation, which, in turn, contributes to increased labor productivity and greater economic returns at manufacturing enterprises [11]. To address problems of this scale, universal automatic control systems with broad functionality, flexible architecture, and ease of use are in demand.

In response to the above-described industrial demand, the programmable logic controller (PLC) was developed–a specialized computing module designed for building distributed automatic control systems. As demonstrated in several studies [12], the PLC has proven itself to be one of the most reliable and effective tools for implementing industrial automation algorithms. Its use ensures:

- high immunity to electromagnetic interference and adverse operating conditions;
- configuration flexibility and easy scaling with changing process parameters;
- reduced design and commissioning time for automated systems.

Integrating a PLC into the design of the lifting mechanism under study can dramatically reduce the impact of human error, improve industrial safety, and significantly improve production efficiency. This approach should be considered a scientifically substantiated step in the gradual digitalization of lifting and transport operations on automobile assembly lines.

A programmable logic controller (PLC) is a specialized industrial computing system that operates on principles similar to the architecture of general-purpose digital computers, but is optimized for the implementation of real-time process control algorithms. PLC operation is based on the execution of user control programs, which provides configuration flexibility and adaptation to changing production conditions [13–16]. Unlike relay circuits, traditionally used for discrete control, PLCs exhibit significantly higher response speeds, stable timing characteristics, and extensive integration capabilities with various actuators [17].

Since their industrial adoption in the 1970s, PLCs have become widespread in various economic sectors—from embedded and transportation systems to electric power, the chemical industry, and high-tech manufacturing [18]. Their reliability under conditions of elevated temperatures, intense vibration, and electromagnetic interference has led to their use in safety-critical systems, including power generation, transportation, and heavy industry [19]. In the context of the Industry 4.0 concept, PLCs are considered as a key element of cyber-physical production systems, ensuring the transition to intelligent automation, digital twins and integration into distributed control networks [20].

The key technological challenge of the process under study is associated with the operation of a lifting mechanism (LM) in a fully mechanical control mode, where the operator is solely responsible for all device actions. The lack of automated safety circuits and emergency shutdown systems creates an increased risk of injury and industrial accidents. Statistics indicate a significant level of industrial injuries at enterprises where the human factor predominates, especially when personnel with insufficient work experience are involved [20].

This approach to control contradicts modern industrial safety requirements and reduces the overall efficiency of the production cycle. In particular, the high probability of operator error when handling loads weighing up to several tons significantly increases the likelihood of damage to products and process equipment.

This study aims to minimize the impact of human error and improve industrial safety through the development and implementation of a PLC-based automated control system for a lifting mechanism. A programmable logic controller (PLC) enables the integration of functions previously implemented by multiple relays, timers, and discrete control devices into a single module [21]. This unification ensures:

-reduction of hardware redundancy and simplification of the control structure;
-increased reliability and fault tolerance of the production process;
-the ability to flexibly modify algorithms without significant capital expenditures.

Given that the equipment under study had not previously been automated, the development of an adaptive PLC implementation architecture, including safe shutdown algorithms, load monitoring, and real-time fault diagnostics, is of particular importance.

Automation of the assembly line using a PLC will ensure a sustainable reduction in accidents, eliminate the critical consequences of human error, and pave the way for the subsequent digital transformation of the production process. Implementation of this approach is consistent with the strategic goals of Industry 4.0, integrating mechanical equipment into a unified intelligent Industrial Internet of Things system and enhancing the overall competitiveness of the enterprise in the high-tech manufacturing market.

The automation technology chosen for implementing the automated assembly line control system was an industrial automation method based on a programmable logic controller (PLC), a recognized global standard for building multifunctional process control systems. The use of a PLC allows for the creation of a hierarchically organized, modular control system with a minimum number of additional peripheral components, capable of scaling depending on the complexity of the production process. The controller is installed in a specialized control cabinet located in close proximity to the process facility, reducing the length of cable connections and increasing the system's electromagnetic immunity.

Developing software for a PLC is a high-tech engineering challenge, driven by both industrial safety requirements and the need to consider the complex topology of the production process.

• Industrial safety factor. Controlling a lifting mechanism handling large loads is potentially associated with the risk of emergency situations. Consequently, the controller's software code must possess the highest degree of fault tolerance, eliminating the possibility of incorrect operation, which requires strict adherence to the principles of functional reliability and the IEC 61508 standard.

• Hierarchical control structure. The automation object is a complex set of process subsystems (sensor nodes, actuators, monitoring subsystems) combined into a multi-level control architecture. Each element must be described by a separate software module; after which they are integrated into a single algorithm implementing the synchronous interaction of multiple parallel processes [21].

• Integration of multi-process modules. When developing software, it is necessary to ensure the ability to simultaneously process numerous discrete and analog signals, as well as implement interrupt and priority mechanisms, which increases the complexity of programming and requires strict planning of data processing cycles.

PLC Operating Principle: The operation of a programmable logic controller is based on a cyclic algorithm for collecting, processing, and issuing control signals. In the first stage, the PLC reads data from the sensor network (position, speed, vibration sensors, and emergency switches). The received signals are converted to digital format and processed according to the user's application program, after which control commands are generated and sent to the actuators—drives, relays, and actuators [22].

Consequently, the PLC acts as a central computing unit, providing a closed-loop control system (sensor-controller-actuator). Its operational characteristics (polling cycle time, memory capacity, throughput) directly determine the requirements for the selection of electrical components and sensor systems [23].

PLC software is its functional core: without user code, the controller is simply a hardware platform. The efficiency of the automated process is largely determined by the quality and optimality of the developed software code.

• Software code is created taking into account the specific features of a specific technological process, including the characteristics of the actuators and the specific electromechanical loads.

• Complex production facilities require the development of a hierarchically structured algorithm that ensures not only the execution of basic process operations but also emergency handling, self-diagnostics, and function redundancy.

• The search for the best automation strategy therefore comes down to finding the optimal PLC software architecture, which must be reliable, scalable, and adaptable to possible changes in the production line configuration.

As a result, the implementation of a PLC in a project ensures comprehensive automation of the process cycle, combining data collection, processing, and actuator control functions into a single multi-level system. The scientific and practical significance of this solution lies in the creation of a fault-tolerant hardware and software system capable of long-term operation under high mechanical and electromagnetic loads [24].

The designed assembly line automation system involves a multi-level implementation architecture, allowing for several alternative physical implementation scenarios, each characterized by a different balance of capital expenditures, technological complexity, and operational benefits.

In a classic industrial design, the automated handling and lifting system is implemented using a ring-shaped (closed) path for the load-bearing module, which moves along an I-beam guide beam with a continuous contour—either circular or elliptical. The geometric parameters of the ring-shaped contour are determined by the length of the lifting mechanism's support beam (LM) and the maximum radius of curvature permissible for the safe movement of the trolley carrying the payload.

However, implementing such a configuration entails significant capital expenditures, as it requires the complete dismantling of existing straight I-beam structures and the installation of reinforced guides with a non-standard profile. The manufacture of custom rolled or cast I-beams exceeding standard dimensions (6 m or more) significantly increases the cost of the study due to the need for specialized design, casting, and subsequent thermomechanical processing. Therefore, a life cycle economic analysis clearly indicates a multiple increase in investment costs when implementing the ring line option.

From a production logistics perspective, the ring line offers a number of functional advantages:

- Continuous traffic flow, reducing the likelihood of collisions;
- Possibility of organizing multi-level routing and buffering.

At the same time, critical limitations have been identified:

- Reduction in the number of intermediate waiting stations for LMs due to the closed loop;
- Complexity of dispatching algorithms and synchronization of movement of multiple lifting modules;
- Increased risk of downtime during emergency shutdown of individual segments of the trajectory.

These factors lead to increased algorithmic complexity of the system software. Developing PLC control programs to ensure safe and optimal closed-loop LM motion requires the construction of multilayer models of synchronous and asynchronous interactions, which significantly increases design and verification costs.

Due to these circumstances, a standard straight-line assembly line configuration was chosen as the project's base configuration, providing a more balanced balance of cost, reliability, and scalability.

For this configuration, at least two LM motion control algorithms are being developed:

1. A synchronous algorithm, which assumes strict coordination of the movements of all lifting modules within a single time cycle;
2. An asynchronous algorithm, which allows for independent operation of the modules while maintaining system-wide safety and performance constraints.

Furthermore, the design documentation includes a set of additional adaptive routines designed to handle non-standard production scenarios (e.g., line operation during a partial or complete shutdown of the main flow). These modules expand the system's functionality, ensuring fault tolerance and dynamic process reconfiguration without interrupting the entire production cycle. Thus, the proposed study develops a scientifically sound concept for intelligent assembly line automation that combines the requirements of economic feasibility, technological reliability, and algorithmic adaptability, consistent with modern industrial engineering principles and the Industry 4.0 paradigm.

The objective of the experimental phase of the study is to identify optimal automated control algorithms, which, following pilot testing, will be implemented in serial operation on a metalworking machine tool assembly line. The methodological basis of the study includes iterative testing and comparative analysis of various hardware and software architecture configurations.

For controlling the lifting mechanisms (LM), several computing resource allocation options are being considered:

- Centralized scheme – one PLC serving the entire production line.
- Decentralized scheme – two PLCs dividing functions by zones or process stages.
- Modular scheme – four PLCs, each controlling a separate LM.

Selecting a specific configuration requires an analysis of the technical and economic tradeoffs between capital expenditures and the complexity of implementing the control algorithm. Using a single PLC reduces equipment costs but leads to increased complexity of the software logic, as a single controller must simultaneously process all signals and synchronize the operation of each lifting module. The initial phase involves the use of a centralized architecture with a single PLC. Pilot tests will include step-by-step verification, followed by testing of a dual-controller configuration to assess the system's resilience to increased loads and its scalability.

The transmission of control signals and process data between the controllers will be studied in two ways:

- via trolleybuses, which provide high noise immunity under dynamic conditions;
- via standard wired connections with shielding and redundancy.

Experimentation is expected to determine the optimal data transmission protocol that ensures the required reliability, low latency, and compliance with industrial real-time standards (e.g., Profinet or EtherCAT).

Full automation of the line requires mechanical reconfiguration of the lifting module, primarily the winch assembly. Two approaches were considered for this study:

1. Complete replacement of the winch with a specialized design optimized for the automated transport of car bodies;
2. Modernization of existing equipment, minimizing capital expenditures while maintaining operational reliability.

Together with leading company specialists and the engineering and design team at the SaryarkaAvtoProm plant, a decision was made to thoroughly modify the existing winch mechanism design. The final project, presented in the form of working design documentation, includes a number of changes aimed at reducing parasitic lateral oscillations of the load-gripping device relative to the main LM motion path.

These oscillations, stochastic and unpredictable in nature, were a key obstacle to the implementation of automated control, as they significantly reduced positioning accuracy and created the risk of emergency situations. The new design ensures dynamic motion stabilization, which is critical for the correct operation of PLC algorithms and the implementation of full automation principles. The presented data demonstrate that the proposed experimental design approach combines engineering reconfiguration of equipment with step-by-step comparative testing of control architectures, which enables the scientifically based implementation of an industrial automation system that meets modern Industry 4.0 standards for reliability, safety, and cost-effectiveness.

To achieve the target objective of suppressing parasitic vibrations in the lifting mechanism's metal structure, a comprehensive research and development program was implemented, including a multi-criteria comparison of alternative design options. A series of experimental and analytical tests were conducted in collaboration with leading specialists from the host company, testing numerous configurations with varying geometric parameters, rigidity characteristics, and manufacturing costs. The selected solution optimally balances the requirements of process reliability, minimized production costs, and compliance with the operating conditions of an automated assembly line.

A detailed vibrodynamic analysis revealed that the primary natural vibrations of the structure occur primarily during the linear horizontal movement of the lifting module between workstations. This mode is accompanied by cyclic accelerations and inertial loads, which, combined with the elevated position of the load, create resonant effects on the metal frame. A critical stage is the movement of the lifting mechanism in its extreme upper position, where the amplitude of vertical oscillations increases due to the maximum inertial force arm.

The designed metal structure implements a spatial rigidity system that ensures the static stability of the lifting mechanism during horizontal movement. A key element is the rigid connection of the steel tubular elements in the upper zone of the structure. The increased flexural rigidity of the pipes prevents the development of oscillatory modes, thereby eliminating the transmission of vibrations to the operating units during movement between stations.

After completing the horizontal movement and positioning the lifting module at the work station, vibration disturbances completely attenuate, as confirmed by the results of full-scale tests. Consequently, the conditions for the implementation of a high-precision automated control system are fully met: resonant oscillations are eliminated, and dynamic effects are reduced to a level that does not affect the operation of the sensors and actuators. The presented design demonstrates a balance between engineering simplicity and vibration resistance, meeting the requirements of industrial automation in the Industry 4.0 paradigm and ensuring reliable operation of the lifting mechanism under high loads and continuous production cycles (see Drawing 1).

Drawing 1 – Sensors location

To ensure precise control of the spatial position of the modified lifting structure, a multi-level sensor architecture was developed, forming the basis of an automated control system. This architecture integrates various types of sensors specialized for measuring linear and angular coordinates, as well as for performing emergency diagnostics and shutdown functions.

As part of this study, a branched network of measuring nodes was implemented, rationally distributed across the load-bearing elements of the winch module. The network configuration was determined based on the criteria of maximum data reliability with minimal signal transmission delay, which is critical for real-time systems.

1. Altitude positioning sensors.

- Mounted on the upper section of the vibration-damping structure, directly integrated into the chain hoist.
- Provide continuous monitoring of the vertical coordinates of the lifting mechanism (LHM) and generate input data for adaptive control of the lifting and lowering speed.

2. Horizontal position sensors.

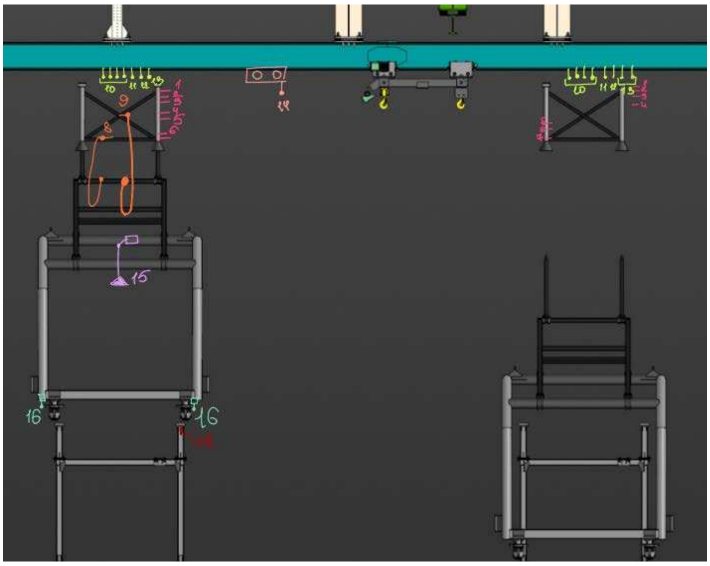
- Mounted on an I-beam in the area of the technological projections, which act as trigger elements.
- Upon contact with the sensor nodes attached to the LHM, the function of determining the current linear position and calibrating spatial coordinates is activated.

3. Support arm condition sensors.

- Mounted directly near the moving arms of the LHM.
- Monitor the kinematic condition of the supports, generating signals for stabilization algorithms and preventing mechanical overloads.

The sensor network is integrated into a single industrial-grade digital system, ensuring high noise immunity and self-diagnostics. It includes multi-level emergency sensors designed to immediately shut down the drive in the event of deviations from permissible motion parameters, including overload, unauthorized movement, and vibration anomalies. Control signals and telemetry are transmitted via industrial real-time protocols (e.g., PROFINET or EtherCAT), ensuring minimal response latency (see Drawing 2).

Based on the analysis, it can be concluded that the developed sensor infrastructure provides highly accurate three-dimensional monitoring necessary for the reliable operation of the automated line and creates the foundation for the subsequent integration of adaptive control algorithms and predictive diagnostics within the Industry 4.0 concept.



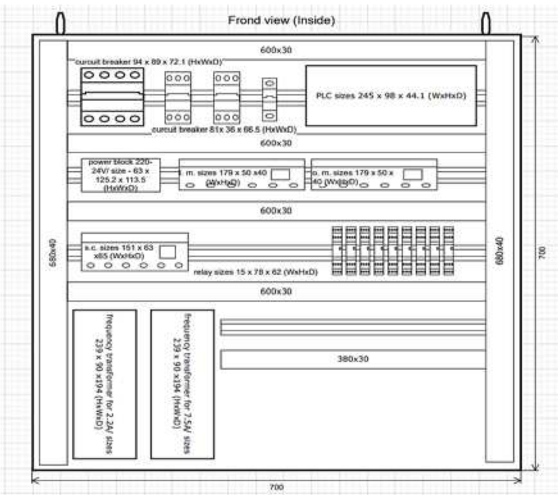
Drawing 2 – Control cabinet

The control cabinet is the central functional module that coordinates and controls the entire process. Each lifting and handling mechanism (LHM) is equipped with an individual control cabinet, eliminating the need to run long signal and control lines outside the individual mechanism. Wiring is localized directly within the cabinet, reducing electromagnetic interference, increasing the reliability of signal transmission, and simplifying maintenance.

The cabinet's interior includes a full range of electrical components necessary for monitoring and control functions: circuit breakers, control relays, frequency converters, stabilized power supplies, and a programmable logic controller (PLC) with input/output modules. All components are selected based on the specifics of the process line and the calculated operating loads, ensuring compliance with industrial electrical safety and reliability standards.

A key feature of the design is the strict weight limitation of the cabinet. Since the structure is located at a height of approximately 8 meters and suspended by a chain hoist, the total equipment weight must be within the permissible lifting capacity of the lifting mechanism. This dictated the selection of a minimum set of electrical components and the use of lightweight structural materials for the housing.

The developed system features a scalable architecture. The number of programmable logic controllers can be varied depending on production requirements and process parameters. Alternative communication channels are provided for data exchange between the PLCs: a wired trolleybus line for transmitting discrete signals and industrial-standard wireless communication interfaces. This modularity ensures the system's adaptability to changing operating conditions and simplifies future upgrades (see Drawing 3).



Drawing 3 – PLC SPECIFICATIONS

For the industrial implementation of the developed automated system, a Mitsubishi Q series programmable logic controller (PLC) was selected as the basic control element. It offers the necessary computing power, configuration flexibility, and expandability for long-term operation in industrial production environments. This class of PLC is characterized by high reliability, support for a modular architecture, and full compatibility with industrial communication protocols, ensuring stable operation under conditions of vibration, temperature fluctuations, and electromagnetic interference.

To ensure complete hardware and software integration, all peripheral and auxiliary components of the hardware environment were selected from Mitsubishi Electric's industrial equipment line, which is fully compatible with the Q series PLC. This approach ensures interface standardization, optimal compatibility of I/O modules, and reduces system setup and maintenance time.

The key element of the PLC is the central processor, which determines the performance, speed, and scalability of the control system. The project utilizes the Mitsubishi Q03UDVCPU processor, which features expanded RAM and non-volatile memory, creating the necessary reserves for future modifications and updates. This additional memory capacity allows for the unlimited implementation of new functional modules, the addition of code blocks, and the refinement of control algorithms without replacing the underlying hardware.

The choice of this architecture is justified by the requirements for reliability and long-term adaptability of the system, which aligns with modern industrial automation principles and the concept of flexible manufacturing within the Industry 4.0 paradigm (see Drawing 4).

Model	Program capacity	Device capacity (Standard device +Standard RAM)	Standard ROM capacity	No. of I/O points	Basic operation processing speed (LD instruction)	Peripheral connection ports*1	Memory card I/F
Q26UDVCPU	260K steps	700K words (60K+640K)	4102K bytes		1.9 ns	USB Ethernet	SD memory card (SD memory card, SDHC memory card) *2
Q13UDVCPU	130K steps	572K words (60K+512K)	2051K bytes			USB Ethernet	
Q06UDVCPU	60K steps	424K words (40K+384K)	1025.5K bytes			USB Ethernet	
Q04UDVCPU	40K steps	168K words (40K+128K)				USB Ethernet	
Q03UDVCPU	30K steps	126K words (30K+96K)				USB Ethernet	

Drawing 4 – Processor Q03UDVCPU

To implement an industrial automated control system for lifting and handling equipment (LHM), a modular hardware configuration was developed based on a Mitsubishi Electric Q-series programmable logic controller (PLC). In addition to the central processing unit (CPU), the PLC architecture utilizes a base unit, which provides the physical and logical integration of all functional modules of the system. A Q62P module, featuring stable voltage and current characteristics, is used as the PLC bus power source, which is critical for reliable system operation in industrial environments with high levels of vibration and electromagnetic interference.

To facilitate interaction with process equipment, specialized discrete input and output modules were incorporated into the design: a QX80 module for receiving control pulses from various types of sensors (including position sensors, emergency stop sensors, and vibration monitoring), and a QY80 module for generating output control signals for drive and actuator operations. This configuration ensures system scalability and the ability to quickly modify control algorithms without major hardware modifications. A Siemens SIMATIC S7-1200 PLC-based simulation environment was used for preliminary software and algorithmic verification of the developed solutions, enabling independent verification of the algorithms and software code.

The simulation was performed in 3D digital twin mode, requiring no additional peripheral modules other than the base processor unit.

Results. During virtual testing, fully automated movement of loads between process stations was realized with minimal operator intervention: intervention was limited to activating two control commands. The operation of the lifting mechanisms was asynchronous but mutually coordinated, ensuring accurate reproduction of the motion logic of real LHMs on an industrial assembly line.

Analysis of the obtained data allowed us to formulate the following key conclusions:

1. Functional adequacy: the simulation model reliably reproduces the kinematic and logical characteristics of the operation of lifting and transport mechanisms, typical of a real production process. 2. Algorithm Verification: The results confirmed the correctness of the developed LHM automatic positioning algorithm and its suitability for implementation in industrial conditions.

3. Software Code Testing: The PLC software verification demonstrated its stable operation and compliance with industrial reliability and fault tolerance requirements.

4. Simulation Limitations: Despite the approximate nature of the 3D model (not completely identical to the actual LHM in terms of weight, dimensions, and dynamic parameters), the simulation provided a qualitative assessment of the algorithms' performance and demonstrated the system's operating principles.

5. Applicability to Real-World Production: It was established that the presented software and algorithmic system provides the required degree of automation and can be scaled for serial production.

Following the completion of the modeling stage, an economic analysis of the feasibility of industrial implementation of the automation system was conducted. The calculations were performed for a standard equipment life cycle of seven years and include the full set of capital and operating costs, as well as projected productivity gains, reductions in unit costs, and changes in the selling price of the vehicles. Summary technical and economic indicators, including profitability calculations and the payback period, are presented in Table 1.

Table 1 – Calculation of Economic Efficiency for the Entire Standard Service Life of the Acquired Equipment

№	Indicators	2025 2 months	2026 12 months	2027 12 months	Total in 26 months	2028	2029	2030	2031	Total for the period of operation of the purchased equipment
1	Total project costs, million tenge	113.75	273.0	68.25	455.0	0	0	0	0	455.0
2	Expenses in %	25.0	60.0	15.0	100.0	0	0	0	0	*
3	Average monthly expenses, million tenge	56.87	22.75	5.69	17.5	0	0	0	0	*
4	Increased productivity in cars per month due to automation of the production process, cars per month	268 (calculation for 1 month only) 1 month installation and setup of equipment	3 216	3 216	6,700	3216	3216	3216	3216	19564
5	Cost of 1 vehicle, calculation using only project funds for automation (grant + co-financing), thousand tenge	424.4	84.9	21.2	67.9	0	0	0	0	23.3

Continuation of Table 1

6	Selling price of 1 car, thousand tenge (price $10,000 x 455 tenge per $1)	4550.0								
7	Selling price of 1 car, taking into account the improvement in car quality due to the use of AI, thousand tenge	4777.5								
8	Including through improved quality thousand tenge	0	227.5	227.5	227.5	227.5	227.5	227.5	227.5	*
9	Profitability per 1 car, thousand tenge	-424.4	+142.6	+206.3	+159.6	+227.5	+227.5	+227.5	+227.5	+120.5
10	Profitability before corporate tax, %									417.2%
11	CIT, 20%									24.1
12	Profitability per 1 car, thousand tenge									96.4
13	Profitability after CIT, %									313.7%

The economic analysis showed that the total costs of project implementation amounted to 455.0 million tenge, with the largest share of expenses incurred during the first year of deployment. In the following years, no additional costs were required, which demonstrates the financial stability and rationality of the investment. Over the entire service period, productivity increased by 19,564 vehicles, confirming a significant improvement in line performance after automation.

The cost of producing a single vehicle was reduced more than 18 times – from 424.4 thousand tenge at the beginning of operation to an average of 23.3 thousand tenge throughout the project. At the same time, the selling price, taking into account the improved quality of vehicles, increased to 4,777.5 thousand tenge, ensuring sustainable profitability growth. The profit per unit of production reached up to 227.5 thousand tenge.

The project's profitability before corporate income tax amounted to 417.2%, and after taxation – 313.7%. These indicators confirm the high economic efficiency of the automated system and the rapid return on investment. Thus, the project has demonstrated not only its technical feasibility but also its financial viability, providing a solid basis for scaling similar solutions across all production lines of the enterprise.

Discussion. In today's world, the automation of manufacturing processes is becoming increasingly relevant and necessary. Automation systems make it possible to significantly increase productivity, reduce labor and material costs, and improve product quality.

Of particular importance is the automation of suspended lifting mechanisms on automotive assembly lines. It accelerates the assembly process, minimizes the human factor, and reduces the likelihood of errors and accidents. The developed control system based on a Programmable Logic Controller (PLC) ensures stable operation of the mechanism, enhances safety, and eliminates workplace accidents associated with manual operation.

Moreover, automation reduces operating costs by lowering equipment wear and improving reliability. Personnel previously involved in moving vehicle bodies can be reassigned to more complex tasks, further improving overall production efficiency.

The development and implementation of such systems require a professional approach, a comprehensive analysis of production needs, and a careful design of operating algorithms. Nevertheless, the simulation results confirmed that the proposed PLC algorithm and program code enable successful automation of this process, opening up prospects for further improvements and scaling of the system.

Conclusion. The study implemented the automation of a mechanical lifting mechanism, which initially consisted of a simple electrical circuit. The project, carried out using a Programmable Logic Controller (PLC), demonstrated the potential to improve the safety, reliability, and efficiency of the production process. The developed algorithms and program code proved their operability in simulation conditions and can be adapted for real-world implementation.

Future improvements to the system are planned through the integration of more advanced control technologies, which will further increase the productivity of the assembly line. Based on the developed algorithms and programs, it is possible to create a universal PLC software solution suitable for nearly all suspended lifting mechanisms. This opens up prospects for applying the developed system in various sectors of the economy related to load handling and aerial cargo transfer.

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