RECENT J. (2026), 79:051-059
https://doi.org/10.31926/RECENT.2026.79.051

Improving Reliability of an Automotive Robotic Assembly Workstation through Mechanical Redesign and Automation Optimization

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Abstract
The increasing level of automation in the automotive industry has significantly improved manufacturing productivity, product quality, and operational consistency. However, highly automated production systems require efficient maintenance strategies to ensure equipment availability and minimize production downtime. This study presents a technical approach for reducing maintenance costs and improving the operational reliability of an automotive product assembly line. The research focuses on one workstation, identified as the critical bottleneck due to its high maintenance expenses, extended downtime, and repeated failures of a collaborative robotic system responsible for the screw-tightening operation. A systematic engineering analysis was performed to identify the principal causes of equipment failures, evaluate workstation functionality, and assess the impact of maintenance-related interruptions on production efficiency. Based on the obtained results, one technical solution is proposed: the replacement of the existing collaborative robot with a more suitable robotic solution capable of supporting the operational requirements of the assembly process. The proposed improvements are evaluated from both technical and economic perspectives. The results demonstrate a significant reduction in maintenance interventions, equipment downtime, repair costs, and production losses while increasing workstation availability and overall manufacturing efficiency. The study highlights the importance of integrating mechanical redesign and automation optimization into predictive maintenance strategies for modern automotive manufacturing systems.

Keywords
predictive maintenance, collaborative robot, automation, manufacturing optimization

1. Introduction

The automotive manufacturing industry is continuously evolving towards highly automated production environments characterized by increased flexibility, digitalization, and intelligent manufacturing systems [1, 2]. Companies are investing substantial resources in robotic automation, collaborative robots (cobots), and smart manufacturing technologies [3, 4] to increase productivity while maintaining high quality standards and reducing operational costs. Although automation considerably improves manufacturing performance, it also introduces new maintenance challenges [5]. Robotic equipment operates continuously under demanding production conditions, where repetitive movements, mechanical loads, and intensive operating cycles gradually increase component wear. As a result, maintenance activities become a critical factor influencing equipment availability, production continuity, and overall manufacturing costs.

Modern maintenance management is no longer limited to repairing equipment after failures occur. Instead, industrial companies increasingly adopt preventive and predictive maintenance strategies that focus on identifying potential failures before they interrupt production [6, 7]. These approaches reduce unplanned downtime, improve equipment reliability, extend component lifetime, and optimize maintenance resources. Within automotive assembly lines, even a single workstation characterized by frequent failures may significantly reduce the overall production performance. Since manufacturing processes are organized as interconnected operations, the interruption of one station often generates production bottlenecks, decreases throughput, increases labor costs, and negatively affects delivery performance.

The present research investigates a maintenance optimization case study conducted on automotive product assembly line. The assembly line consists of multiple automated workstations performing sequential operations, including ultrasonic welding, leak testing, electrical testing, sensor assembly, pump installation, and final cover tightening. A previous analysis of the production line identified workstation W15 as the most critical maintenance point due to its exceptionally high repair costs and prolonged production downtime. The workstation employs a Universal Robots UR3 collaborative robot [8] responsible for tightening the service cover using an industrial screwdriver. Continuous exposure to the screwdriver's weight generates excessive mechanical stress on the robot joints, leading to repeated failures and costly maintenance interventions.

The objective of this research is to develop and evaluate engineering solutions capable of improving the reliability of workstation W15 while reducing maintenance costs and increasing production availability. One technical solution is investigated: the implementation of an alternative robotic solution better suited to the workstation requirements. The proposed methodology combines functional analysis, root cause identification, engineering redesign, automation optimization, and economic evaluation to determine the effectiveness of the proposed improvements. The obtained results contribute to the broader field of intelligent maintenance management by demonstrating how targeted mechanical modifications and optimized robotic systems can significantly enhance manufacturing performance while reducing operational costs.

2. Literature Review

Maintenance management has become one of the most important factors influencing productivity, equipment availability, and manufacturing competitiveness in modern industrial systems [9]. As production lines become increasingly automated, companies must ensure high levels of equipment reliability while minimizing maintenance costs and production interruptions. Consequently, maintenance has evolved from a corrective activity into a strategic function integrated within modern manufacturing systems [10, 11].

Maintenance strategies are generally classified into corrective, preventive, predictive, and condition-based maintenance. Corrective maintenance is initiated strictly after equipment has failed occurs and is typically associated with higher repair costs, unexpected production downtime, and reduced operational efficiency. Preventive maintenance consists of scheduled inspections and replacement of components before failures occur. Although this approach significantly reduces breakdown frequency, unnecessary interventions may increase maintenance costs when components are replaced before reaching the end of their useful life. Predictive maintenance represents the latest stage in maintenance evolution. It relies on continuous monitoring of equipment conditions through sensors, operational data analysis, and intelligent algorithms capable of identifying degradation before failures occur [12, 13]. By aligning maintenance schedules with the actual condition of equipment rather than fixed calendars, these strategies lower both maintenance expenses and production losses.

Industrial robotics has become a key element in manufacturing automation due to its ability to perform repetitive operations with high precision and consistency. Collaborative robots (cobots) [14, 15] have attracted particular interest because they can safely operate alongside human workers while requiring less installation space than conventional industrial robots. Their flexibility makes them suitable for assembly, inspection, packaging, machine tending, and quality control applications.

Despite these advantages, collaborative robots may experience reliability issues when they are continuously subjected to loads close to their mechanical limits. Repetitive movements combined with excessive payloads increase wear in robot joints, gearboxes, and actuators, leading to higher maintenance frequency and reduced equipment lifetime. Therefore, proper robot selection according to payload, cycle time, workspace, and operational requirements is essential for ensuring long-term manufacturing efficiency.

Within automotive manufacturing, robotic workstations are frequently integrated into assembly lines producing fuel delivery systems, electronic components, exhaust after-treatment systems, and electrification technologies. Since these production lines operate under high-volume manufacturing conditions, even short periods of equipment downtime may generate considerable economic losses.

Consequently, maintenance optimization has become closely connected with production engineering and workstation design. Recent industrial research [16] emphasizes that mechanical redesign can often provide significant maintenance improvements without requiring complete production line replacement. Supporting heavy end-effectors through pneumatic balancing systems, optimizing robot trajectories, reducing inertial loads, and selecting robots with higher payload capacities represent effective engineering approaches for extending equipment lifetime while maintaining production performance.

The present research follows this engineering philosophy by combining maintenance analysis with workstation redesign. Rather than treating equipment failures exclusively as maintenance problems, the study investigates their mechanical causes and proposes technical modifications intended to eliminate the source of repeated failures. This integrated approach contributes to both maintenance optimization and production system reliability.

3. Research Methodology

This research was conducted as an industrial case study within an automotive manufacturing facility. The objective was to identify the workstation responsible for the highest maintenance costs and to develop technical solutions capable of improving equipment reliability while reducing production downtime. The research methodology consisted of five sequential stages.

Stage 1 – Production System Analysis. The entire assembly line was analyzed to identify workstation performance, maintenance history, production interruptions, and operational dependencies. Maintenance records, downtime reports, repair costs, and production data were evaluated to determine the stations with the greatest impact on manufacturing efficiency. The layout of the analyzed assembly line is presented in Figure 1. The simulation was performed using the Plant Simulation software – Tecnomatix from Siemens Digital Industries Software [17].

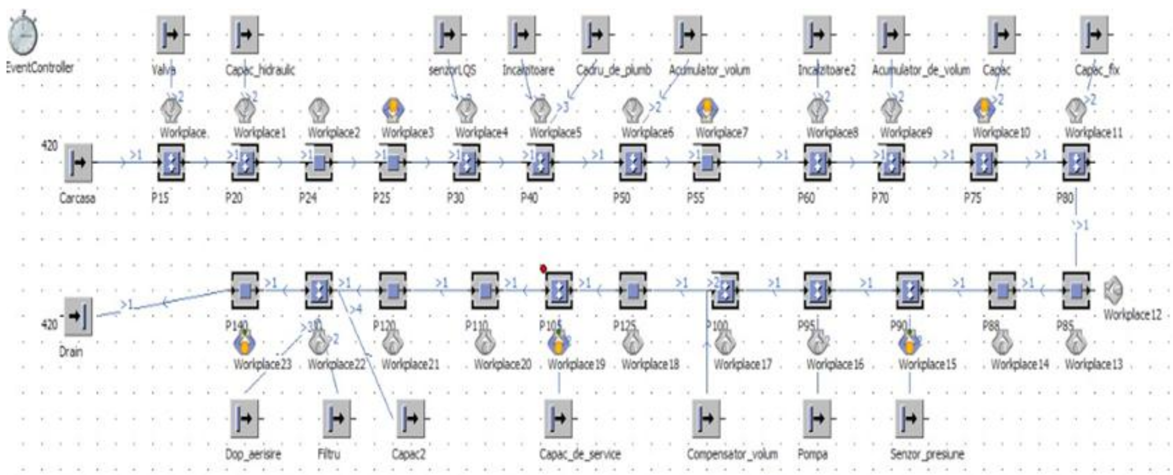

Fig. 1. Tecnomatix representation of assembly line

The simulation allowed the analysis of the assembly process and allowed the identification of operational problems, such as blockages, failures, operating times, auxiliary waiting times (Figure 2). The analysis demonstrated that workstation K15 generated the highest maintenance costs and the longest production interruptions, making it the primary candidate for improvement.

Stage 2 – Functional Analysis of the Workstation. The operational sequence of workstation K15 was examined in detail. Particular attention was paid to the interaction between the collaborative robot, the electric screwdriver, and the service cover during the tightening process. The workstation employs a Universal Robots UR3 [8] collaborative robot responsible for positioning and operating the screwdriver used to fasten the service cover of the unit. Continuous repetitive movements combined with the weight of the end-effector were identified as the principal source of excessive mechanical loading applied to the robot joints.

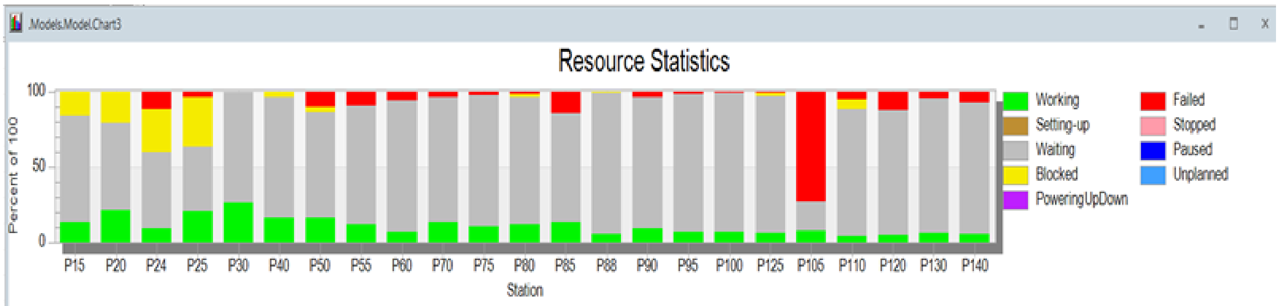

Fig. 2. Production Simulation (P105 = K15)

Stage 3 – Root Cause Identification. A structured engineering analysis was performed to determine the origin of the recurrent failures affecting the robotic workstation. Mechanical loading conditions, robot characteristics, maintenance records, operational cycles, and equipment configuration were evaluated to identify the underlying causes responsible for repeated maintenance interventions. The study demonstrated that the excessive mechanical stress generated by the screwdriver significantly accelerated wear in the robot joints, resulting in increased maintenance frequency and prolonged equipment downtime.

Stage 4 – Development of Technical Solutions. Based on the identified causes, one engineering solutions was developed. The solution proposes replacing the existing collaborative robot with an alternative robotic system better suited to the operational requirements of the workstation, offering improved payload capacity, durability, and long-term reliability. The main criteria considered in selecting the most appropriate robotic system for the workstation are summarized in Figure 3.

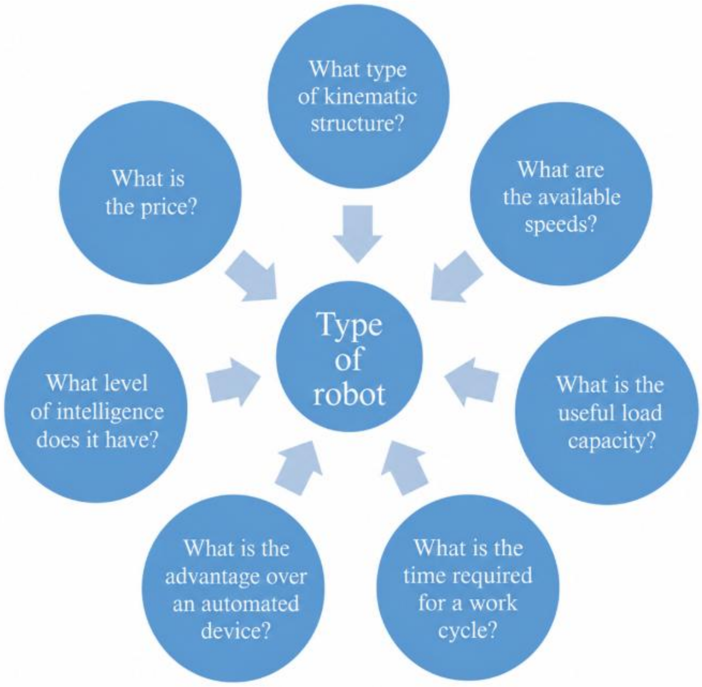

Fig. 3. Criteria of Robot Type Selection

Stage 5 – Technical and Economic Evaluation. Finally, the solution was assessed from technical and economic perspectives. The evaluation considered maintenance costs, equipment availability, expected downtime reduction, operational reliability, production continuity, and potential long-term financial benefits. This methodology enables a comprehensive assessment of the relationship between workstation design, maintenance performance, and manufacturing efficiency while providing practical engineering recommendations applicable to automated automotive production systems.

4. Analysis of the K15 Robotic Workstation

The preliminary maintenance analysis identified workstation K15 as the most critical station within the assembly line. Compared to the remaining workstations, K15 exhibited the highest maintenance costs, the longest downtime periods, and the lowest operational availability. Consequently, this workstation was selected as the focus of the present research. The primary function of workstation K15 is the installation and tightening of the service cover mounted on the unit. This operation represents one of the final assembly stages and directly influences both product quality and production continuity. Any interruption occurring at this station immediately affects downstream operations, reducing the overall throughput of the manufacturing line.

The assembly process is performed by a collaborative robotic system equipped with an industrial electric screwdriver. The robot positions the screwdriver above the service cover and sequentially tightens the fastening screws according to predefined torque parameters. Accurate positioning and repeatability are essential because improper tightening may lead to leakage, assembly defects, or product rejection. The assembly integrates the pumping system, pressure regulation components, electronic sensors, service cover, and sealing elements into a compact module designed for automotive exhaust after-treatment applications. Although the workstation itself performs only the tightening operation, its reliability is essential because the service cover seals the complete unit. Any interruption during assembly may generate production delays, quality issues, or additional manual interventions.

4.1. Functional Description of the Existing Robotic System

The existing workstation employs a Universal Robots UR3 collaborative robot responsible for manipulating the electric screwdriver used during the tightening operation. The robot performs repetitive movements while maintaining strict positioning accuracy required by the assembly process. Its collaborative architecture enables safe operation in proximity to human operators without requiring extensive safety fencing. According to the equipment specifications, the UR3 collaborative robot provides a payload capacity of 3 kg and a working radius of 500 mm, making it suitable for precision assembly operations performed within compact manufacturing cells. The robot incorporates force and torque sensors that allow safe human–robot collaboration while simplifying programming and production changeovers.

Despite these advantages, the operational requirements of workstation P105 differ considerably from the robot's optimal working conditions. During every production cycle, the robotic arm must continuously support the industrial screwdriver while performing repetitive tightening movements. As a consequence, the combined effects of repetitive motion, tool inertia, and continuous payload generate substantial mechanical stress on the robot joints. Unlike occasional handling operations, the screw-tightening cycle is repeated throughout every production shift, accumulating millions of joint movements during normal equipment operation. This continuous loading accelerates mechanical wear within the robotic arm and progressively reduces the service life of critical components.

Maintenance reports collected during production confirmed that the majority of failures occurred in the robot joints rather than in the screwdriver or auxiliary equipment. Joint replacement represented the most frequent maintenance intervention and generated significant repair costs together with prolonged production interruptions.

These observations indicate that the principal limitation of the workstation is not the control system itself but rather the mechanical loading conditions imposed on the collaborative robot. Consequently, improving the mechanical configuration of the workstation became the primary objective of the proposed engineering solutions. Instead of increasing maintenance frequency, the present research aims to eliminate the root mechanical causes responsible for repeated robotic failures through workstation redesign and equipment optimization.

4.2. Root Cause Analysis

Following the functional analysis of workstation K15, a systematic root cause investigation was performed to determine the factors responsible for the recurrent failures affecting the collaborative robotic system. Instead of focusing solely on the failed components, the analysis examined the interaction between the robot, the tooling, the assembly process, and the operating environment in order to identify the mechanisms leading to premature equipment degradation.

An Ishikawa (fishbone) diagram was employed as the primary qualitative analysis tool because it enables the classification of potential causes into several categories, including machine, method, material, manpower, measurement, and environment. This structured approach facilitates the identification of the most influential factors contributing to equipment failure while supporting the development of targeted engineering solutions. The potential root causes contributing to the high maintenance costs of the existing robotic system are illustrated in the Ishikawa diagram presented in Figure 4.

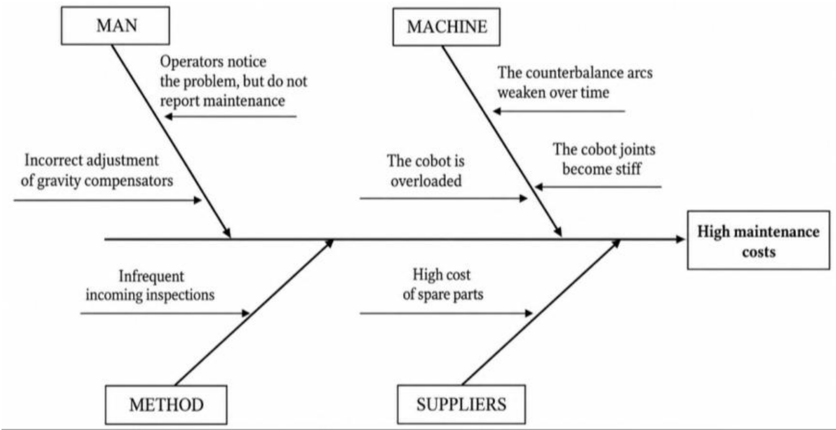

Fig. 4. Ishikawa analysis

The analysis demonstrated that the dominant causes originated from the machine category. The collaborative robot continuously supported the weight of the electric screwdriver while simultaneously executing repetitive tightening cycles. Unlike conventional pick-and-place operations, the tightening process requires the robot to maintain a stable position while transmitting reaction forces generated during screw fastening. Consequently, both static and dynamic mechanical loads acted repeatedly on the robot joints throughout every production cycle.

A second contributing factor was related to the method used for performing the operation. The workstation design required the robot to manipulate the screwdriver during the entire assembly sequence without any auxiliary mechanical support. As a result, the robotic arm remained permanently loaded even when no tightening operation was actively performed. From the maintenance perspective, repeated joint replacements restored the robot to operational condition but did not eliminate the mechanical causes responsible for the failures. Therefore, maintenance activities solved the consequences of the problem rather than its origin.

The environmental and human factors showed only minor influence on equipment reliability. Operators followed standardized procedures, while production conditions remained stable throughout the observation period. Likewise, no significant quality issues related to supplied materials or assembly components were identified. The Ishikawa analysis therefore indicated that the recurrent failures originated primarily from excessive mechanical loading of the collaborative robot rather than from operator errors or inadequate maintenance practices. These findings justified the development of engineering solutions focused on reducing the forces acting on the robotic arm instead of merely increasing maintenance frequency.

The obtained results also support an important maintenance engineering principle: equipment reliability can often be improved more effectively through workstation redesign than through additional corrective maintenance interventions. Eliminating the source of mechanical stress increases component lifetime while simultaneously reducing repair costs and production interruptions.

4.3. Integration into the Existing Assembly Line

One of the principal objectives of the redesign was to minimize production disruption during implementation. Therefore, the proposed robotic system was selected so that it could be integrated into the existing workstation architecture without major modifications to adjacent equipment. The replacement maintains the original operational sequence of workstation K15. The robot continues to perform the positioning and tightening operations required for the installation of the service cover on the unit. Consequently, no changes are required in the upstream or downstream production stations.

Only the robotic manipulator and its associated programming require adaptation. Existing tooling, pneumatic components, positioning fixtures, safety devices, and quality verification procedures remain compatible with the redesigned workstation configuration. This significantly reduces commissioning time while limiting implementation costs. Furthermore, maintaining the existing assembly logic minimizes operator retraining requirements and allows production personnel to rapidly adapt to the upgraded workstation.

5. Results and Discussion

5.1. Expected Operational Improvements

Replacing the existing robotic system is expected to improve workstation performance in several areas. The most significant improvement concerns equipment reliability. Because the proposed robot operates with a larger mechanical safety margin, the stress acting on its joints during repetitive tightening cycles is considerably reduced. This directly decreases the probability of premature mechanical failures.

A second expected improvement is the reduction of unplanned production downtime. Since robotic joint failures represented the primary cause of maintenance interventions at workstation P105, increasing robot durability contributes directly to higher production availability. Operational stability is also expected to improve. Reduced structural deformation during screwdriver manipulation allows more consistent positioning accuracy, leading to improved tightening quality and reduced process variability.

From the maintenance perspective, the redesigned workstation simplifies maintenance planning by reducing the frequency of emergency interventions. Maintenance personnel can increasingly focus on scheduled preventive activities instead of corrective repairs, improving maintenance resource allocation throughout the production facility. Finally, the improved workstation contributes to greater production flexibility. The higher payload capability provides additional capacity for future tooling upgrades or process modifications without exceeding the mechanical limitations of the robotic system.

5.2. Technical Evaluation and Economic Benefits

The proposed engineering solution was evaluated from the perspective of equipment reliability, maintenance performance, and production continuity. The solution increases the mechanical robustness of the workstation through the implementation of a robot better suited to continuous industrial operation. Rather than relying on a single corrective measure, the proposed approach combines mechanical redesign with equipment optimization. This integrated strategy significantly increases the probability of achieving sustainable long-term improvements.

Beyond the technical improvements, the proposed redesign generates substantial economic benefits. The reduction in robotic joint failures decreases expenditure associated with spare parts, emergency maintenance interventions, and external repair services. Since robotic joint replacement represents one of the most expensive maintenance activities affecting workstation K15, extending joint lifetime produces significant financial savings.

A second source of economic benefit results from improved production availability. Every avoided equipment failure eliminates production interruptions, reduces idle time, and minimizes the need for manual replacement of automated operations. The improved reliability of workstation K15 also reduces indirect manufacturing costs associated with production rescheduling, overtime work, quality inspections, and delayed deliveries. Another important financial advantage is the reduction of maintenance workload. Maintenance engineers can allocate more time to preventive maintenance activities instead of emergency corrective interventions, increasing overall maintenance efficiency across the production facility. Although implementing a pneumatic balancing system and replacing the collaborative robot require an initial capital investment, the long-term reduction in maintenance costs and productivity losses is expected to compensate for these expenses within the operational lifetime of the equipment. This demonstrates that investing in engineering improvements can provide measurable economic value beyond immediate maintenance savings.

6. Conclusions and Future Research

The objective of this research was to investigate the causes responsible for the high maintenance costs associated with workstation K15 of an automotive unit assembly line and to propose engineering solutions capable of improving equipment reliability while reducing operational expenses. The maintenance analysis demonstrated that workstation K15 represented the most critical station within the production line due to its frequent robotic failures, extended downtime, and elevated repair costs. Detailed functional analysis revealed that the principal cause of these failures was the excessive mechanical loading generated by the continuous manipulation of an industrial electric screwdriver by the collaborative robot. This loading accelerated joint wear and significantly reduced the operational availability of the workstation.

A structured engineering methodology combining functional analysis, root cause identification, workstation redesign, and technical evaluation was applied to address these challenges. Two complementary technical solutions were developed. The first solution introduced a pneumatic balancing mechanism designed to support the weight of the screwdriver, thereby reducing the mechanical forces transmitted to the robotic arm. This relatively simple modification minimizes joint loading without requiring substantial changes to the existing production equipment. The second solution proposed replacing the existing collaborative robot with a robotic system offering improved payload capacity and greater mechanical robustness. Operating below its maximum capacity, the new robot is expected to experience significantly lower mechanical stress, resulting in increased reliability, longer maintenance intervals, and improved production continuity.

The combined implementation of these engineering solutions provides multiple technical and economic benefits. Expected improvements include: reduction of robotic joint failures; lower maintenance and spare-part costs; decreased production downtime; increased workstation availability; improved process stability and product quality; enhanced production efficiency through higher equipment reliability.

From an industrial perspective, the study demonstrates that maintenance optimization should not rely exclusively on increasing maintenance frequency or replacing failed components. Instead, greater long-term benefits can be achieved by eliminating the engineering causes responsible for repeated failures through workstation redesign and appropriate equipment selection. The presented methodology may be applied to similar automated manufacturing systems where repetitive robotic operations generate excessive mechanical loading and increased maintenance costs. Consequently, the research contributes to the development of more reliable, efficient, and economically sustainable production systems within the automotive industry.

Although the proposed engineering solutions significantly improve workstation reliability, several research directions may further enhance maintenance performance and production efficiency.

Future work may focus on integrating predictive maintenance technologies capable of continuously monitoring robot health through vibration sensors, motor current analysis, temperature monitoring, and artificial intelligence algorithms. These technologies could identify early signs of mechanical degradation before failures occur, allowing maintenance interventions to be scheduled proactively.

Another promising research direction involves the creation of a digital twin of workstation P105. A digital twin would enable virtual simulation of robotic movements, mechanical loads, and maintenance scenarios under different production conditions, supporting continuous process optimization without interrupting manufacturing activities.

Machine learning techniques could also be incorporated into maintenance decision-making systems to predict component lifetime based on historical maintenance records and real-time operational data. Such intelligent maintenance systems represent an essential component of Industry 4.0 manufacturing environments. Finally, future studies may evaluate the applicability of the proposed engineering methodology to other robotic workstations performing assembly, welding, material handling, or inspection operations, allowing broader validation of the proposed maintenance optimization approach.

Acknowledgements

The authors would like to express their sincere appreciation to the management and engineering personnel involved in the industrial case study for providing technical information and practical insights that supported this research.

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