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Collaborative Robot in Engine Assembly: A Socioeconomic Approach to Technological Advancement in Manufacturing

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ABSTRACT

Industry 4.0 enabling technologies have been integrated into manufacturing systems. One of these technologies, the collaborative robot or cobot, holds significant expansion potential due to its shared application with humans in manufacturing environments. It offers cost reduction, a safer working environment, especially regarding ergonomic risks, and product quality improvements. This research aimed to assess the economic and social benefits, focusing on the reduction of ergonomic risks and quality gains resulting from the implementation of cobots in the engine assembly process. A case study was conducted in an engine assembly company, involving process observation, data collection, analysis of technical reports, and interviews with managers. The results indicated that integrating cobots into the manufacturing process is advantageous for the industry. There was a significant reduction in annual operating costs, totalling $41,602.56, leading to a return on investment in 1 year and 9 months. Furthermore, ensuring torque in the correct sequence resulted in product quality improvement, reduced ergonomic risks, and a safer working environment for operators. This research contributes to advancing knowledge on the economic, social, and quality advantages of cobot application in the engine assembly process.

1 | Introduction

Technological advancement and the increasing demand for efficiency and competitiveness have spurred industries to adopt innovations to enhance their processes. Industry 4.0, known as the fourth industrial revolution, is characterised by the integration of emerging technologies that bridge the physical and digital dimensions of manufacturing environments. These technologies include the Internet of Things, automation and robotics, human-machine interaction, and artificial intelligence, among others [1]. Among the innovations, the implementation of collaborative robots (cobots) stands out in creating more flexible production systems [2]. Cobots are low-cost, easy to set up, and programme, and safe to use alongside human workers [3]. Cobots are valuable assistants that operate in shared workspaces with humans, supporting industrial automation efforts that are essential for modern manufacturing, especially in addressing the ongoing challenges of process improvement and customer satisfaction [4].

In recent years, collaborative robotics has played an increasingly strategic role in transforming manufacturing systems. The integration of human flexibility with robotic precision has proven effective in improving productivity, safety, and process balance [5]. Studies also emphasise that understanding the dimensions of human-robot interaction dimensions is essential to enhance collaboration quality and operator performance [6].

In terms of layout and planning, Nourmohammadi et al. [7] demonstrated that adopting U-shaped configurations and higher levels of human-robot collaboration can reduce the number of stations, cycle time, and operational costs. Constraint programming has shown better results than traditional mixed-integer linear programming approaches when modelling complex scheduling problems, particularly when cost factors related to cobots, grippers, and human operators are considered [8].

Safety and ergonomics are also central to current research. Kheirabadi et al. [9] proposed a model that incorporates zoning rules and safe task assignments, reducing collision risk while maintaining production efficiency. Pickard and Elkington [10] showed that trust and ease of use are critical for acceptance in collaborative environments, especially in ergonomically demanding sectors such as composite manufacturing. Performance-based interaction models have also been developed to help manufacturers assess key collaboration indicators, considering human-centric factors such as trust, engagement, situational awareness, and ergonomic safety [6].

A literature review on cobots in assembly indicated findings in terms of technology, productivity, and ergonomics in cobot adoption in assembly processes. Studies have reported the use of technologies supporting cobot integration in assembly. Intelligent technologies and autonomous systems remove people from monotonous and repetitive tasks, allowing them to focus on knowledge-based work [11]. New technologies and system integration help meet the increased demand in production [12]. Cobot adoption has been on the rise in the manufacturing industry [2]. The interface between humans and cobots in assembly has been analysed through augmented reality [13]. Assembly planning and adaptive control of the cobot were carried out in real time through a digital twin system [14]. A neural network-based system in the assembly process recognised the tasks performed by the operator to create a collaborative assembly plan capable of autonomously commanding the cobot tasks [15].

Other research highlighted gains in productivity and quality. Cobot in electrical harness assembly reduced process cycle time and costs [16]. Workers and cobots can be integrated into an assembly line to improve process balancing [17]. Human-robot collaboration in product assembly and the use of Virtual Reality increased measurement accuracy through skeletal hand tracking [18]. Collaborative work between robots and humans optimised the assembly of pneumatic cylinders [19].

Ergonomics was another aspect highlighted in studies on cobots in manufacturing. Cobots improve assembly performance and mitigate potential occupational risks, enhancing organisational performance efficiency and reducing costs [20]. Cobots have been introduced into assembly processes to mitigate ergonomic risks, improve productivity [4], and reduce absenteeism [21]. Cobot reduced ergonomic risk in electrical harness assembly [22], shoe polishing [23], and homo-kinetic joint assembly [24]. In collaborative assembly processes, humans and robots safely share the same workspace in various tasks such as picking and positioning parts, assembly, material handling, and inspection [25].

The findings described above refer to studies that addressed cobots in the assembly process. However, no literature was identified specifically evaluating cobots in the assembly of internal combustion engines. This identified gap in the literature suggests the following research question: What advantages does the use of cobots in the assembly of internal combustion engines provide to companies? Internal combustion engines play a crucial role in the automotive and energy industries, with engine assembly being the process that adds the most value to the final product. Therefore, gains in this production stage are amplified. This study aimed to evaluate the economic, ergonomic, and quality advantages obtained from using cobots in the assembly of internal combustion engines.

This study was conducted through a literature analysis on the use of cobots in assembly processes, identifying factors demonstrating advantages for companies. Additionally, a case study was conducted in an internal combustion engine assembly operation to assess the gains obtained due to the implementation of cobots in this process.

Engine assembly presents unique challenges that combine mechanical precision, strict torque sequencing, and tight spatial constraints. Human workers are typically responsible for managing these complex tasks while adapting to model variations and maintaining safety and ergonomics. In this context, collaborative robots offer a targeted solution: they automate repetitive and physically demanding steps without requiring significant layout changes or safety barriers, which is especially valuable in engine assembly lines with limited space. This distinctive scenario sets cobot integration in engine assembly apart from other industries, where applications may involve simpler or more flexible tasks.

This article is structured in six sections. Next, the literature review on cobots is presented in Section 2; materials and methods used are in Section 3; results of the case study are described in Section 4; discussion in Section 5; and the final considerations and research contributions in Section 6.

2 | Literature Review

During this stage of the research work, a search was conducted in databases for articles addressing the theme of the economic and social analysis of the use of cobots in engine assembly.

2.1 | Definition of Cobot

Cobots are collaborative robots that play a significant role in Industry 4.0 and smart manufacturing. Known for their ability to interact safely with operators in a shared workspace [21], cobots represent a substantial evolution from autonomous industrial robots. In contrast to these robots, cobots can closely interact with operators due to the use of programming software that creates virtual safety surfaces, known as a safety envelope. This allows cobots to be in proximity to operators without compromising safety [26].

Manufacturing systems involve both machines and human operators, where productivity and ergonomic performance are crucial aspects. Despite the increasing automation, many manufacturing processes are still carried out manually, such as in automotive assembly lines [12].

The application of cobots in the manufacturing process, along with the safety envelope defining the workspace of the robot is illustrated in Figure 1.

In human–robot collaboration, it is crucial to develop motion planning algorithms for wheeled mobile manipulators that ensure flexibility, efficiency, and safe operation without collisions [27]. In Dahl et al. [28], different models of collaboration between humans and cobots are addressed, emphasising the direct influence of the type of interaction on the process safety level. The discussed models are as follows:

- Coexistence: The human operator and the cobot share the same environment but generally do not interact.
- Sequential collaboration: The human operator and the cobot work in the same work-space but at different times.
- Cooperation: The human operator and the cobot work in the same workspace simultaneously but focus on separate tasks.
- Responsive Collaboration: The human operator and the cobot perform a task together, where the actions of one have immediate consequences on the other. This activity is monitored by special sensors and vision systems.

The collaboration models between humans and cobots are illustrated in Figure 2.

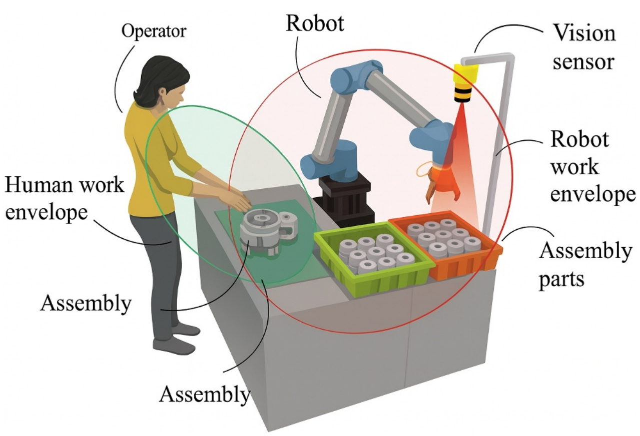

FIGURE 1 | Application of cobots in the manufacturing process.

2.2 | Cobot in Engine Assembly

A literature review was conducted to investigate the advantages of using cobots in engine assembly. Content analysis revealed that the evaluation criteria for this technology include economic, social, and quality factors.

Most selected articles addressed the economic aspect, even if not directly related to financial considerations. Many articles presented indirect gains, such as increased productivity, contributing to economic benefits in the use of cobots in engine assembly. In Cohen et al. [21], the authors analysed the return on investment in implementing a cobot, comparing its performance with that of a human. The results showed a return of $612,500, and for the cobot implementation to be viable, implementation costs should be at most $250,000. As $612,500 is greater than $250,000, the cobot implementation was considered justified in the study.

Dimitrokalli et al. [18] found that the average completion time for the case assembly process, with cobot assistance, is 303.3 s, while without the cobot, it is 313.6 s. This indicates that assembly with a cobot is faster, providing a productivity advantage. During the

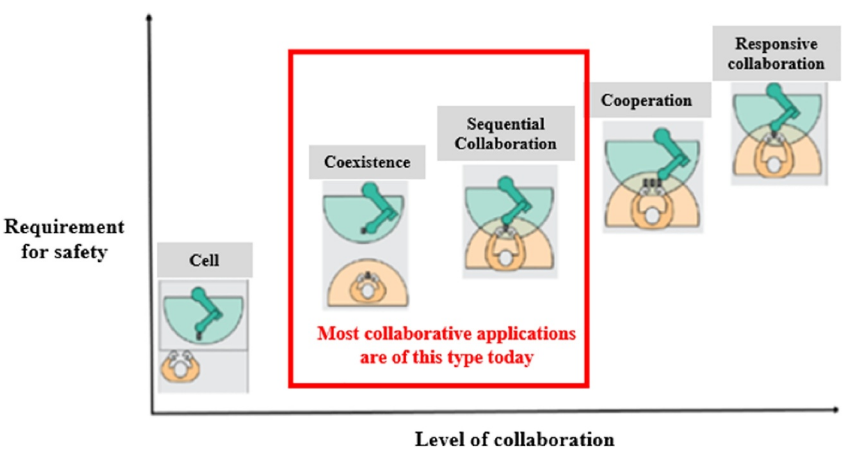

FIGURE 2 | Collaboration models between humans and cobots.

COVID-19 pandemic, there was an increased demand for mechanical ventilators. Industries responded to this need by using cobots in production as an alternative. This approach helped reduce the total manufacturing process time and ensure the required production volume [3].

Román Ibáñez et al. [16] proposed the use of cobots in a wire-winding process. In the case study, a cycle time reduction from 38 to 28 s was observed. Comparatively, while manual activity resulted in a maximum of 757 wire coils per shift, the proposed method was able to produce 1028 coils. Cherubini et al. [24] emphasised that the successful implementation of cobots in a manufacturing process can lead to a rapid return on investment. In an experiment conducted in an automotive company, the savings obtained were able to cover hardware and configuration costs in approximately 1 year.

Realyvásquez-Vargas et al. [20] showed that the introduction of cobots resulted in a 15.46% decrease in production cycle time, reducing from 9.7 to 8.2 s per piece. This represented a productivity increase of 18.3% in the company. Dalle Mura and Dini [29] highlighted that the collaborative process between humans and robots represents a significant revolution in the industry, resulting in increased robot productivity with human flexibility.

Salunkhe et al. [2] demonstrated in an experiment in the wheel nut torque process a reduction in cycle time from 145 s in manual operation to 107 s with the use of cobots. Quenehen et al. [19] introduced the cobot in non-value-added activities, such as moving parts. This resulted in a reduction in the final cycle time from 44.5 to 42.1 s, transferring this task from the operator to the cobot. Cobots have internal safety mechanisms, eliminating the need for external safety devices, and allowing for the advantages of both manual and automated manufacturing in a combined production system [17].

The social aspect was addressed in some articles with a focus on ergonomic benefits when introducing cobots into the production process. Román Ibáñez et al. [16] demonstrated ergonomic gains in the process of tying electrical harnesses. In the manual process, the RULA score was evaluated as 7 on the scale, indicating high risk. After the alteration, a new assessment was conducted, and the score reduced to 3. The RULA tool works on a scale from 1 (low risk) to 7 (high risk).

Zhang et al. [4] compared two workflows: manual and collaborative. In the manual process, the operator performed multitasking, increasing the exposure time to operational risks. In the collaborative flow, a cobot was introduced to mitigate ergonomic risks. The use of cobots not only significantly improved employee safety but also brought the factory closer to zero accidents [21]. In a production scenario, it was demonstrated that the implementation of cobots in the assembly process reduced the average total risk from 111.1 to 84.2, representing a 24.21% reduction in wrist tension [18].

During the Covid-19 pandemic, maintaining social distancing in industrial areas was a challenge. In a production scenario for hospital ventilators, the use of cobots assisted in social distancing strategies in processes [3]. Manual operation compared to collaborative operation increases exposure to ergonomic risk [12].

Quality was also a positive aspect identified in the literature. The use of cobots offers significant advantages for product quality, especially when employed in quality inspection tasks in conjunction with other technologies, such as vision systems. When quality standards are well established, collaboration between the cobot and the vision system can result in a significant reduction in errors during the inspection process. Salunkhe et al. [2] observed substantial quality gains when comparing the manual process with the use of cobots in a wheel nut torque operation. In this study, the quality index increased from 85% to 99.17% with the implementation of cobots.

The studies identified in the literature showed the benefits of cobots in terms of economic, quality, and ergonomic aspects in manufacturing processes. However, the absence of a study on cobots in engine assembly stood out, characterising a gap that was explored by this research.

3 | Materials and Methods

This study focuses on the application of cobots in assembly processes within a diesel engine manufacturing company. The research follows an exploratory approach, combining qualitative and quantitative methods.

Field research was conducted through a case study. The case study method provides an exploratory approach to gain more knowledge about a specific phenomenon. It can be considered such as a linear and interactive process, an empirical investigation that analyses a contemporary phenomenon in the context of real life, considering that the boundaries between the phenomenon and the context may not be clear. Considering the scope of the research project, the chosen method for data collection was the observation of assembly and analysis of process documents. Among the analysed documents are reports on time studies of the operation, indicators of productivity and quality performance, and ergonomic risk analyses.

The economic evaluation considered the investment required for the acquisition, installation, and integration of the cobot into the manufacturing system. Additionally, costs related to the assembly operation of the oil cooler assembly in the combustion engine were raised before and after the cobot implementation. The social evaluation consisted of comparing the ergonomic risk of activities performed at the focus workstation of the study. The working risk condition of the operator before and after the cobot implementation was assessed using the Humantech system. Quality benefits were quantified through a review of the Failure Mode and Effect Analysis (FMEA). The calculation of the risk priority number considered aspects of severity, occurrence, and detection of failure before and after the cobot implementation.

3.1 | Function of the Oil Cooler

The cooling system in the diesel engine is responsible for maintaining an ideal temperature for its operation by circulating liquid through the block and cylinder head galleries. This liquid is cooled by the radiator through heat exchange with external ventilation. The oil cooler also plays an important role, cooling the lubricating oil through thermal exchange with the coolant. The pump sends the oil to the cooler, where cooling and filtering of the oil occur before being distributed through the oil galleries of the block. On the external part of the cooler, the coolant circulates and undergoes heat exchange with the lubricating oil. Upon returning through the radiator, the liquid enters at a lower temperature.

The oil system passes internally through the cooler, while the cooling system passes through the external side, ensuring the necessary cooling for the proper functioning of the engine.

3.2 | Process Before Cobot Implementation

The study examines the assembly of the oil cooler assembly on the cylinder block in a diesel engine assembly line. The assembly is secured to the block using bolts and studs as shown in Figure 3.

At the workstation, there is an industrial computer with specialised production software. This software displays the parts to be used, the assembly sequence, the model and serial number of the engine, and the devices necessary for assembly as shown in Figure 4.

In the assembly process, the operator initially positions the gasket and the cooling element, then the gasket and the cooler housing and filter assembly, and finally secures the bolts and studs in the oil cooler. The assembly sequence is illustrated in Figure 5.

Because of the size of the oil cooler, it is necessary to follow a predetermined sequence to tighten the bolts with a torque of 33 Nm. This sequence ensures that the cooler is correctly seated and aligned on the gasket, preventing oil or water leaks. The tightening sequence specified by the product engineering is illustrated in Figure 6.

The engine is transported along the assembly line by a conveyor with rubber rollers driven by electric motors. The resources available at each stage of the operation depend on the assembly activity the operator is performing. For the oil cooler assembly,

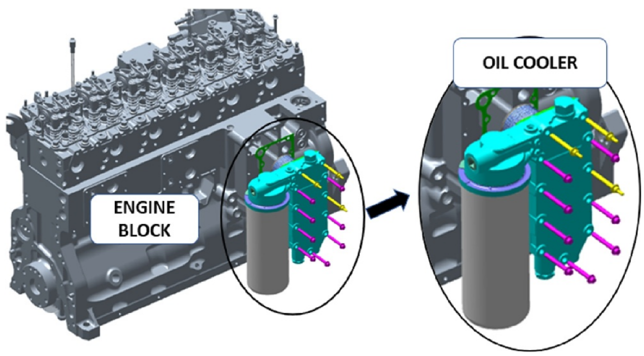

FIGURE 3 | Assembly presentation.

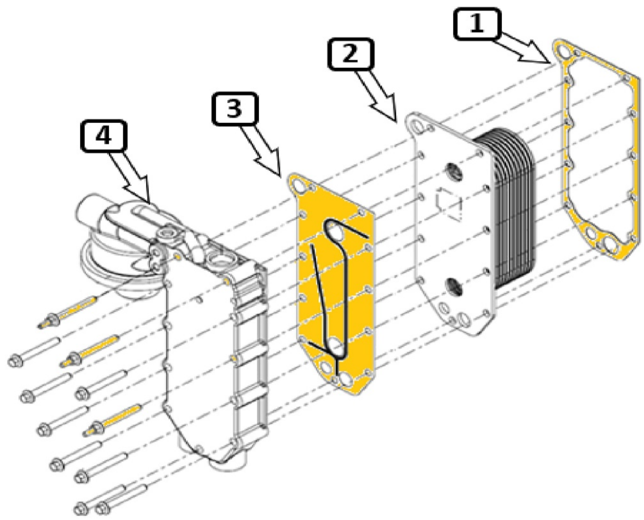

FIGURE 5 | Presentation of the assembly sequence of components.

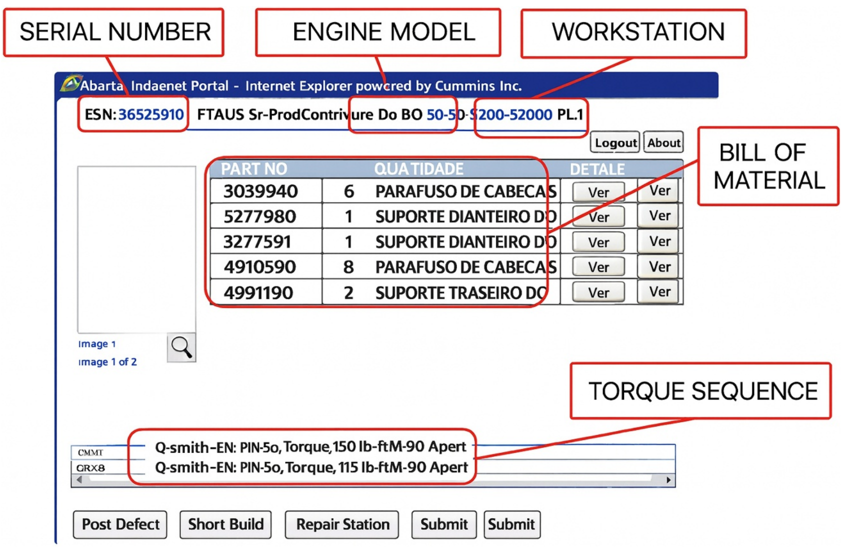

FIGURE 4 | Industrial computer screen with production software.

the operator has guide pins to position the cooler and an electronic tool to apply torque to the bolts and studs of the assembly on the engine block. An overview of the assembly stage is shown in Figure 7.

4 | Case Study

The case study addressed the implementation of a cobot in an engine assembly process. This study was conducted in a multinational American company engaged in the manufacturing of diesel engines, along with involvement in four complementary segments: distribution, manufacturing of components (turbochargers and after-treatment systems), generators, and new energies, with a focus on hydrogen and electrification.

The company is undergoing a transformation process, aiming to implement Industry 4.0 enabling technologies. This transformation process aims to adopt the development of both individuals and processes, to modernise and enhance the company.

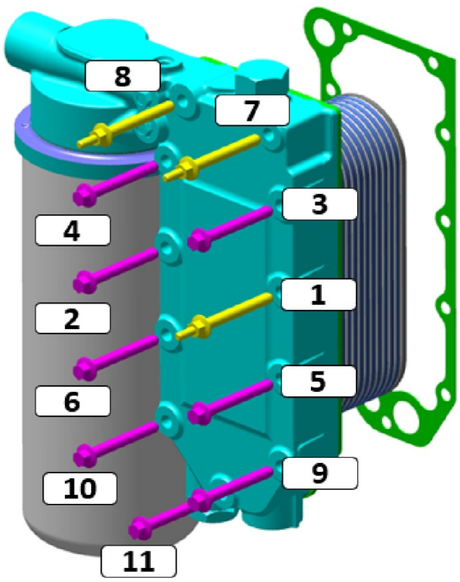

FIGURE 6 | Presentation of the bolt tightening sequence.

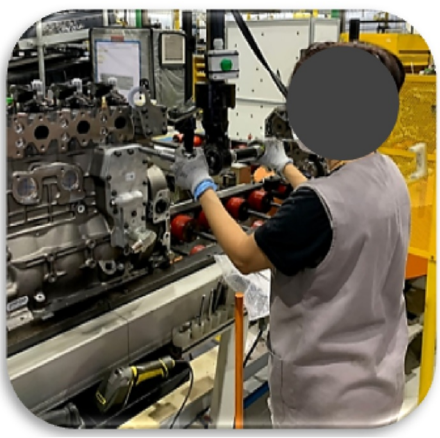

FIGURE 7 | Overview of the assembly process.

4.1 | Cobot Implementation

With a focus on reducing failures in the torque process of the bolts in the oil cooler assembly, the company chose to automate this operation. The project had predetermined financial resources from the headquarters and could not have major modifications on the factory floor. Another requirement was that the solution could operate side by side with the operator without posing health or safety risks in the workplace.

During the search for solutions that would fit the layout of the assembly line, the company chose to use the UR10 model cobot, which has a payload capacity of 10 kg, a reach of 1300 mm, and a weight of 33.5 kg as shown in Figure 8. This solution proved effective as it would help reduce the exposure of the operator to ergonomic risks and gain productivity since the cobot would take over part of the activities of the operator, making it possible to integrate the pre-assembly of the cooler with the assembly line.

The company was looking for a technology that would meet the process requirements without significant investments. Thus, the cobot was integrated into the existing resources. The workstation is illustrated in Figure 9, where the numbering represents the following elements: cobot (1); conveyor driven by servo motors (2); panel with the manufacturing system (3); electronic tool for tightening the bolts of the oil cooler (4).

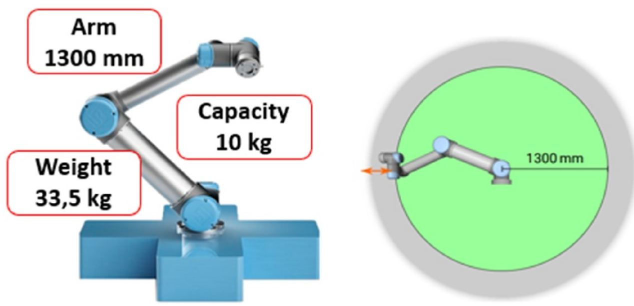

FIGURE 8 | Overview of the UR10 model cobot.

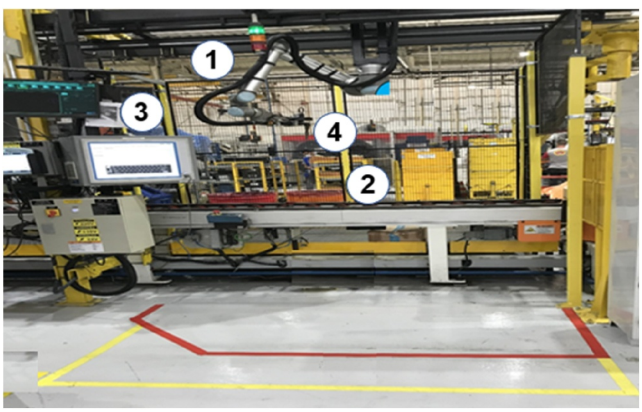

FIGURE 9 | Overview of the workstation.

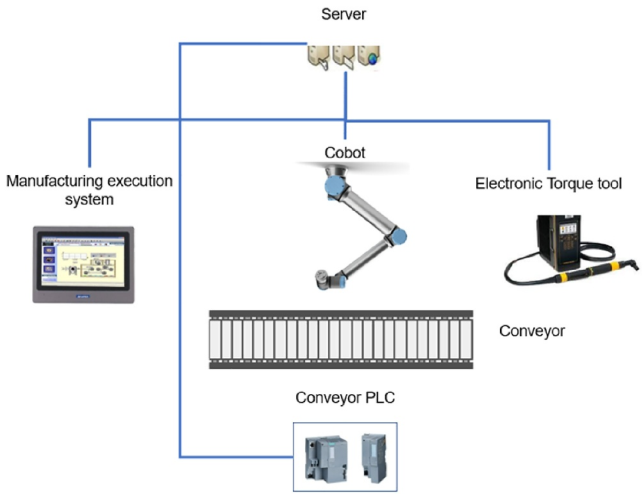

FIGURE 10 | Communication structure between equipment.

A new communication network architecture was necessary to enable the integration and synchronisation of the equipment. For example, the conveyor is controlled by a programmable logic controller connected to the communication network. All other equipment involved in the process also can exchange information with the server, ensuring that each command is executed at the right time for each task. The communication structure between the equipment is shown in Figure 10.

4.2 | Process Capacity

Before the implementation of the cobot, the oil cooler sub-assembly (Operation 100) was carried out at a dedicated workstation located approximately 32 m away from the main assembly line. Once the sub-assembly was completed, the operator had to manually transport the component to the final assembly station, where the oil cooler was mounted onto the engine block (Operation 200) and the bolts were tightened using an electronic torque tool (Operation 300). This setup required two operators and involved nonproductive time due to the transportation of parts between stations.

After the cobot was integrated into the process, the layout was restructured to allow Operations 100 and 200 to be performed by a single operator in the same location, while Operation 300 (torque application) was fully automated by the cobot. This adjustment eliminated the need for physical displacement of the operator, reduced overall process time, and improved work distribution and line balancing.

The integration of Operations 100 and 200 into a single workstation was only feasible with the introduction of the cobot due to space and safety constraints. In the original layout, there was insufficient room for two operators to work side by side at the engine assembly line without compromising ergonomics or workflow. The cobot, however, requires minimal space and can operate safely near a human without physical barriers. This enabled the consolidation of tasks at one station, which would not have been practical under manual operation.

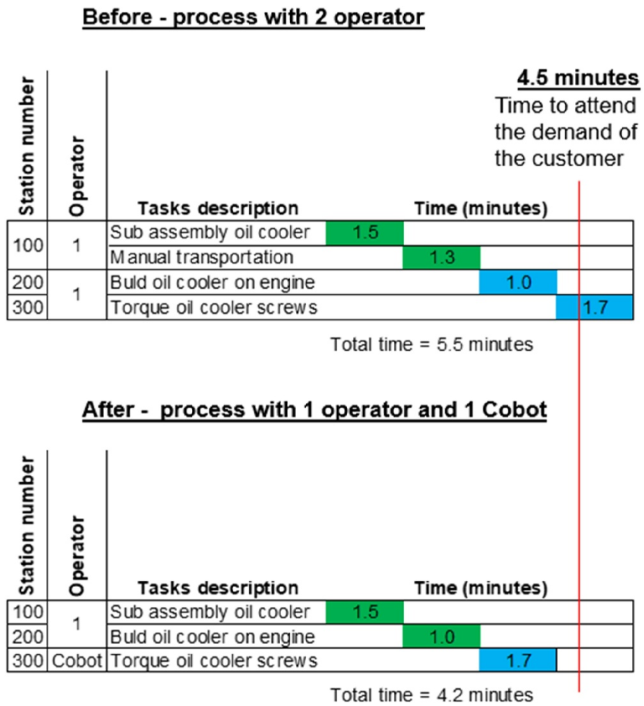

FIGURE 11 | Line balancing to meet customer demand.

To meet production demand, the complete process must be executed in a maximum of 4.5 min per engine. In the original setup, the sub-assembly took 1.5 min, the transport required 1.3 min, the mounting process 1.0 min, and the torque application 1.7 minutes—totalling 5.5 min and requiring two operators. In the new configuration, the operator performs the sub-assembly (1.5 min) and mounting (1.0 min), while the cobot carries out the torque operation in parallel (1.7 min). This optimisation allowed the reallocation of labour to other activities, thereby increasing efficiency. The scenarios before and after the implementation of the cobot are illustrated in Figure 11.

4.3 | Economic Analysis

The analysis of implementing the cobot in the assembly line began with an evaluation of the economic feasibility of this technology model. To achieve this, operational costs and investment data were collected. The investment for this project solely involved the purchase of the cobot and its integration into the assembly line. The cost of the cobot was $52,000.00, and the integration into the assembly line was $16,000.00. Thus, the total project investment amounted to $68,000.00.

The analysis of economic gains considered the reduction in operational costs with the introduction of the cobot. The operational labour cost is $10.83 per hour. The line operates 16 h per day in 2 shifts. The annual calculation of operational costs indicated $41,602.56 per year. This reduction represents an approximate 61.2% decrease in labour-related operating costs for this assembly task. The electricity consumption of the cobot is 0.350 kWh, with the manufacturer comparing its consumption to that of a household appliance. Despite being low, the cost was also considered in the economic analysis. The factory produces approximately 48,000 engines per year, and the cobot is used for 1.7 min per engine cycle, resulting in approximately 81,600 min or 1360 h per year. The cost of electricity per kWh paid by the company is $0.18, totalling $87.58 annually.

Another cost related to the cobot and considered by the company is preventive maintenance. In this case, as it is a new technology, the company opted to contract the service of the manufacturer. The average monthly cost of the service was $320.00 or $4320.00 per year.

The labour cost savings refer to the reallocation of one operator, not two. Although two operators were previously assigned to this part of the process, only one position was effectively optimised by the cobot. Additionally, while the cobot's energy consumption is low, the calculation includes its use even during standby periods, not just while moving. The annual costs of electricity and preventive maintenance were included in the investment analysis to ensure a realistic projection of total cost of ownership. The total investment values and operational reduction per year are presented in Table 1.

TABLE 1 | Total investment cost and annual operational reduction.

Description	Value (USD)
Cobot acquisition	52,000.00
Integration cost	16,000.00
Total initial investment	**68,000.00**
Annual preventive maintenance	4320.00
Annual electricity cost	87.58
Total annual operating costs	**4407.58**

In the cash flow analysis, a positive balance was evident as early as the second year. The disbursement required for project implementation was $72,407.58, resulting in an annual cost reduction of $41,602.56. The cash flow is presented in Table 2.

The return-on-investment calculation revealed that the $72,407.58 invested in the modernisation of the assembly line will be recovered in 1.74 years or 1 year and 9 months. For the company, the shorter the return-on-investment period, the more appealing the project. This was one of the key decision factors in prioritising this project over others that were also requested.

4.4 | Ergonomic Analysis of the Process

The ergonomic factor is also a crucial consideration in the process. The manual screw tightening operation performed by a human required the operator to hold the torque tool in an elevated position for 1.7 min in each assembly cycle. This activity poses risks to the upper limbs, such as arms, shoulders, and wrists, as well as risks to the neck. The new process resulted in a 58% reduction in risk since the torque operation for the oil cooler screws was transferred to the cobot. Thus, modernisation also contributed to a reduction in health risks for human workers. The results of the ergonomic risk analysis before and after the cobot implementation are shown in Figure 12.

The ergonomic analysis software employed by the researched company is the Humantech system, where the result is presented in a Priority Risk Score (PRS) on a scale ranging from 1 to 50. In this engine assembly line, there are 54 workstations subjected to ergonomic assessment. Only 10 out of the 54

TABLE 2 | Cash flow.

Year	Investment (USD)	Savings (USD)	Operating costs (USD)	Net cash flow (USD)	Cumulative cash flow (USD)
0	68,000.00	0.00	0.00	−68,000.00	−68,000.00
1	0.00	41,602.56	4407.58	37,194.98	−30,805.02
2	0.00	41,602.56	4407.58	37,194.98	6389.96

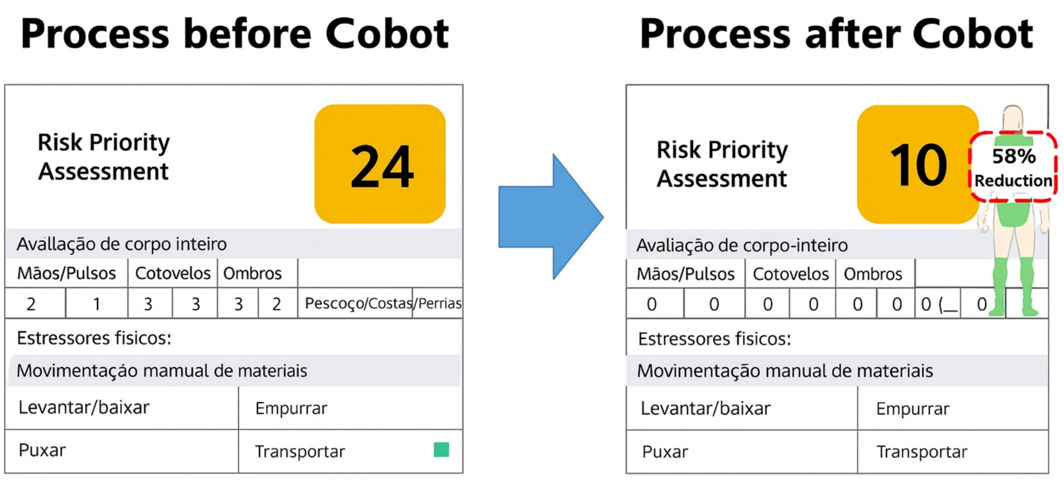

FIGURE 12 | Ergonomic analysis before and after.

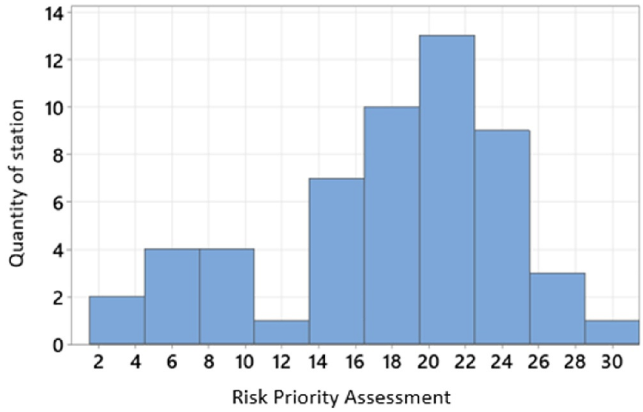

FIGURE 13 | Priority risk score by stage.

workstations have a risk equal to or lower than 10 PRS, accounting for 22.73%. This indicates that the reduction in the score from 24 to 10 PRS due to the implementation of the cobot has made the workstation safer for the worker, contributing to the goal of the company, reducing the risk score of all workstations to equal or less than 10 PRS. The number of workstations grouped by priority risk score is presented in Figure 13.

4.5 | Process Quality Vulnerability

The torque process and the correct seating of the oil cooler assembly on the engine block are crucial for the operation of the system. A failure in this product requirement, such as low torque or incorrect tightening sequence, can lead to leakage between the galleries, causing a mixture of coolant with lubricating oil. The effect of this mixture or external leakage will result in a loss of engine performance, and depending on the quantity, it could even lead to engine failure. To illustrate this situation, Figure 14 shows an oil leak through the fastening holes of the screws (location indicated by the red arrows) due to a torque process failure. This failure occurred in a durability test with the engine already installed in the vehicle.

The implementation of the cobot ensured the application of torque in the correct tightening sequence, reducing the occurrence of failures in the process. The quality risk was quantified through the Failure Modes and Effects Analysis (FMEA). The operation performed by the cobot reduced the occurrence score of the failure mode 'applying torque in the incorrect sequence' from 7 to 2, on a scale from 0 to 10. This result was achieved because the cobot was classified as an error-proof preventive system in the process. This improvement decreased the risk score from 196 to 56 on a scale from 0 to 1000. This corresponds to a 71.4% reduction in the Risk Priority Number (RPN), indicating a substantial decrease in the probability of failure related to incorrect torque application. The Risk Priority Number (RPN) before and after the cobot is shown in Table 3.

5 | Discussion

The implementation of the cobot in the assembly process yielded several benefits for the surveyed company. The study

FIGURE 14 | Oil leak through screw holes.

showcased a reduction in waste, operational costs, and occupational risks, while simultaneously enhancing product quality, assembly line efficiency, and operator safety. These outcomes align with the work of Realyvásquez-Vargas et al. [20], who also observed a reduction or elimination of occupational risks with the introduction of cobots in assembly tasks, subsequently enhancing organisational efficiency. The study revealed that the cobot successfully achieved its objectives.

Another advantage derived from the project was that the implementation of the cobot in the assembly process allowed the proximity of the oil cooler from pre-assembly to the main engine assembly line. This layout change would not have been feasible without the cobot due to space constraints for two operators. By eliminating the need for operator movement between stations, the modification reduced waste related to nonproductive activities, as the time spent by the operator transporting the piece to the assembly line was significantly reduced. Additionally, it enabled line balancing by assigning some operational tasks to the cobot, making the line more efficient. This finding supports the study by Quenehen et al. [19], which address the use of cobots to increase efficiency in operations and the utilisation of techniques such as standardised work and continuous improvement. Additionally, it aligns with the results of Zhang et al. [4], who emphasised productivity improvement due to the implementation of cobots in assembly processes.

In this study, the economic evaluation considered the investment in cobot implementation and the gains from the reduction in operational costs. The analysed values indicated that the project is economically viable, with a return on investment in 1 year and 9 months. These results corroborate the study by Realyvásquez-Vargas et al. [20], in which integrating the cobot

TABLE 3 | Failure modes and effects analysis.

	Process function/ requirement	Potential failure mode	Potential effect of failure	Severity	Potential cause	Prevention	Occurrence	Detection	Detection	RPN	Recommended actions
Process before cobot	Torque oil cooler in the right torque sequence	Torque oil cooler in the wrong torque sequence	Oil leak	7	Process not followed	Work instruction	7	Leak test	4	196	Introduce cobot
Process after cobot	Torque oil cooler in the right torque sequence	Torque oil cooler in the wrong torque sequence	Oil leak	7	Process not followed	Cobot (error proofing)	2	Leak test	4	56	

with the assembly station resulted in a return on investment of 5.29 years. It is worth noting that the time required to achieve a return on investment can vary depending on factors such as the investment amount, integration complexity, and the value of operational gains.

Regarding occupational health and safety, the cobot implementation resulted in a reduction of ergonomic risk, especially in upper limbs such as the neck and arms. This reduction had a positive impact on the quality of life of the workers, preventing work-related musculoskeletal disorders. The results align with the study by Román Ibáñez et al. [16], which demonstrated that the cobot improves the ergonomics of the process for the human worker by removing part of the manual activity and minimising the movements required by the human operator. Furthermore, Salunkhe et al. [2] identified that the cobot successfully eliminated the operation with ergonomic risk performed by the operator.

Moreover, the cobot contributed to an improvement in product quality. The sequence of tightening screws must be strictly followed for the oil cooler assembly to be securely fixed on the engine. However, the operation performed by a human presented a significant potential for failure. The implementation of the cobot mitigated this risk by automating the torque sequence, which led to a notable reduction in the FMEA risk score. It is important to highlight that this quality improvement is based on a preventive risk analysis. Since the cobot implementation is recent, there is not yet sufficient historical production data to quantify the reduction in actual defect rates. Nonetheless, the decrease in the Risk Priority Number (RPN) reflects a lower likelihood of critical failure in the process, reinforcing the cobot's contribution to improving product reliability. The implementation of the cobot eliminated this failure risk, reducing the FMEA risk score. The study supports the findings of Salunkhe et al. [2], who mentioned that the use of cobots in the manufacturing area is beneficial for the assembly station, especially in eliminating quality issues.

Compared to other industries where cobots are used for basic pick-and-place or inspection tasks, engine assembly requires strict sequencing, consistent torque application, and integration with existing manual operations. These constraints elevate the complexity of automation, and the successful deployment of a cobot in this setting highlights its potential in high-precision, space-constrained environments.

Although this study adopted a deterministic approach to economic evaluation, we acknowledge the potential of applying a probabilistic risk analysis in future research. Varying technical and economic assumptions, such as investment values, maintenance costs, and production volumes, could provide a more comprehensive understanding of uncertainties and enhance the robustness of project decision-making.

6 | Conclusions

This study assessed the deployment of cobots in an engine assembly line, providing a comprehensive overview of their economic, social, and quality advantages. The results demonstrated that integrating cobots into the manufacturing process increased efficiency while also improving operator safety and product reliability.

Economically, the cobot reduced operational labour costs and achieved a return on investment in less than 2 years. Quality improvements were observed through a significant reduction in the Risk Priority Number (RPN), indicating greater process reliability. Ergonomically, the cobot minimised worker exposure to repetitive and physically demanding tasks, contributing to a safer and healthier work environment.

Beyond these results, the study offers theoretical contributions by addressing a gap in the literature on cobot applications in engine assembly lines—a context with unique requirements compared to other manufacturing environments. From a managerial perspective, the case demonstrates that cobot implementation is a viable strategy even in scenarios with limited layout flexibility or strict cost constraints. These findings may inform decision-making by production managers, industrial engineers, and technology suppliers.

On a broader level, this research highlights how Industry 4.0 technologies can foster more human-centred and sustainable manufacturing systems. Cobot integration supports not only productivity, but also workforce well-being and skills development. In this sense, the study's implications extend to competitiveness, local economic growth, and the long-term sustainability of the automotive sector.

It is important to note that the findings are based on a single case study in a specific manufacturing environment. Organisational structure, available resources, and technological maturity vary across companies, and thus the results should not be generalised without caution.

Future research should consider comparative case studies across different industrial sectors and levels of technological readiness. Additionally, there is significant potential in exploring more advanced forms of human-cobot collaboration, particularly in dynamic environments supported by AI-based decision systems. These studies could provide a deeper understanding of how such technologies impact not only productivity and ergonomics, but also adaptability, resilience, and sustainability in manufacturing.

Author Contributions

Andre da Silva Martin: conceptualization, methodology, writing – original draft. **Luiz Fernando Rodrigues Pinto:** investigation, methodology, visualization, writing – original draft. **Geraldo Cardoso de Oliveira Neto:** supervision, visualization. **Francesco Facchini:** funding acquisition, supervision, visualization, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Q. Chen, B. Heydari, and M. Moghaddam, "Leveraging Task Modularity in Reinforcement Learning for Adaptable Industry 4.0 Automation," *Journal of Mechanical Design* 143, no. 7 (2021): 071701, https://doi.org/10.1115/1.4049531.

2. O. Salunkhe, O. Stensöta, M. Åkerman, Å.F. Berglund, and P. A. Alveflo, "Assembly 4.0: Wheel Hub Nut Assembly Using a Cobot," *IFAC-PapersOnLine* 53, no. 13 (2019): 1632–1637, https://doi.org/10.1016/j.ifacol.2019.11.434.

3. A. A. Malik and A. Bilberg, "Complexity-Based Task Allocation in Human-Robot Collaborative Assembly," *Industrial Robot* 46, no. 4 (2019): 471–480, https://doi.org/10.1108/IR-11-2018-0231.

4. Y. J. Zhang, L. Liu, N. Huang, R. Radwin, and J. Li, "From Manual Operation to Collaborative Robot Assembly: An Integrated Model of Productivity and Ergonomic Performance," *IEEE Robotics and Automation Letters* 6, no. 2 (2021): 895–902, https://doi.org/10.1109/LRA.2021.3052427.

5. V. Di Pasquale, V. De Simone, V. Giubileo, and S. Miranda, "A Taxonomy of Factors Influencing Worker's Performance in Human–Robot Collaboration," *IET Collaborative Intelligent Manufacturing* 5, no. 1 (2023): e12069, https://doi.org/10.1049/cim2.12069.

6. J. A. Mulet Alberola and I. Fassi, "Analysis of Interactive Manufacturing Systems: Towards a Performance-Based Assessment Methodology," *IET Collaborative Intelligent Manufacturing* 4, no. 4 (2022): 286–298, https://doi.org/10.1049/cim2.12063.

7. A. Nourmohammadi, T. Arbaoui, M. Fathi, and A. Dolgui, "Balancing Human-Robot Collaborative Assembly Lines: A Constraint Programming Approach," *Computers & Industrial Engineering* 205 (2025): 111154, https://doi.org/10.1016/j.cie.2024.111154.

8. Y. D. Demiralay and Y. Kara, "A Cost-Effective Balancing Model for Human-Robot Collaborative Assembly Lines," *Procedia Computer Science* 253 (2025): 2766–2775, https://doi.org/10.1016/j.procs.2025.02.001.

9. M. Kheirabadi, S. Keivanpour, J. M. Frayret, and Y. Chinniah, "Safety-Driven Optimisation of Human–Robot Collaborative Assembly Line Balancing," *International Journal of Production Research* (2025): 1–26, https://doi.org/10.1080/00207543.2025.2469288.

10. L. R. Pickard and M. Elkington, "Laminator Trust in Human–Robot Collaboration for Manufacturing Fibre-Reinforced Composites," *IET Collaborative Intelligent Manufacturing* 6, no. 4 (2024): e12123, https://doi.org/10.1049/cim2.12123.

11. F. D'Souza, J. Costa, and J. N. Pires, "Development of a Solution for Adding a Collaborative Robot to an Industrial AGV," *Industrial Robot* 47, no. 5 (2020): 723–735, https://doi.org/10.1108/IR-01-2020-0004.

12. A. A. Malik, T. Masood, and R. Kousar, "Reconfiguring and Ramping-Up Ventilator Production in the Face of COVID-19: Can Robots Help?," *Journal of Manufacturing Systems* 60 (2021): 864–875, https://doi.org/10.1016/j.jmsy.2020.09.008.

13. C. H. Chu and Y. L. Liu, "Augmented Reality User Interface Design and Experimental Evaluation for Human-Robot Collaborative Assembly," *Journal of Manufacturing Systems* 68 (2023): 313–324, https://doi.org/10.1016/j.jmsy.2023.04.007.

14. S. Liu, X. V. Wang, and L. Wang, "Digital Twin-Enabled Advance Execution for Human-Robot Collaborative Assembly," *CIRP Annals* 71, no. 1 (2022): 25–28, https://doi.org/10.1016/j.cirp.2022.03.024.

15. D. Moutinho, L. F. Rocha, C. M. Costa, L. F. Teixeira, and G. Veiga, "Deep Learning-Based Human Action Recognition to Leverage Context Awareness in Collaborative Assembly," *Robotics and Computer-Integrated Manufacturing* 80 (2023): 102449, https://doi.org/10.1016/j.rcim.2022.102449.

16. V. Román Ibáñez, F. A. Pujol, S. García Ortega, and J. M. Sanz Perpiñán, "Collaborative Robotics in Wire Harnesses Spot Taping Process," *Computers in Industry* 125 (2021): 103370, https://doi.org/10.1016/j.compind.2020.103370.

17. C. Weckenborg and T. S. Spengler, "Assembly Line Balancing With Collaborative Robots Under Consideration of Ergonomics: A Cost-Oriented Approach," *IFAC-PapersOnLine* 52, no. 13 (2019): 1860–1865, https://doi.org/10.1016/j.ifacol.2019.11.473.

18. A. Dimitrokalli, G. C. Vosniakos, D. Nathanael, and E. Matsas, "On the Assessment of Human-Robot Collaboration in Mechanical Product Assembly by Use of Virtual Reality," *Procedia Manufacturing* 51 (2020): 627–634, https://doi.org/10.1016/j.promfg.2020.10.088.

19. A. Quenehen, J. Pocachard, and N. Klement, "Process Optimisation Using Collaborative Robots - Comparative Case Study," *IFAC-PapersOnLine* 52, no. 13 (2019): 60–65, https://doi.org/10.1016/j.ifacol.2019.11.131.

20. A. Realyvásquez-Vargas, K. Cecilia Arredondo-Soto, J. Luis García-Alcaraz, B. Yail Márquez-Lobato, and J. Cruz-García, "Introduction and Configuration of a Collaborative Robot in an Assembly Task as a Means to Decrease Occupational Risks and Increase Efficiency in a Manufacturing Company," *Robotics and Computer-Integrated Manufacturing* 57 (2019): 315–328, https://doi.org/10.1016/j.rcim.2018.12.015.

21. Y. Cohen, S. Shoval, M. Faccio, and R. Minto, "Deploying Cobots in Collaborative Systems: Major Considerations and Productivity Analysis," *International Journal of Production Research* 60, no. 6 (2022): 1815–1831, https://doi.org/10.1080/00207543.2020.1870758.

22. G. E. Navas-Reascos, D. Romero, C. A. Rodriguez, F. Guedea, and J. Stahre, "Wire Harness Assembly Process Supported by a Collaborative Robot: A Case Study Focus on Ergonomics," *Robotics* 11, no. 6 (2022): 131, https://doi.org/10.3390/robotics11060131.

23. G. Chiriatti, M. Ciccarelli, M. Forlini, et al., "Human-Centered Design of a Collaborative Robotic System for the Shoe-Polishing Process," *Machines* 10, no. 11 (2022): 1082, https://doi.org/10.3390/machines10111082.

24. A. Cherubini, R. Passama, A. Crosnier, A. Lasnier, and P. Fraisse, "Collaborative Manufacturing With Physical Human-Robot Interaction," *Robotics and Computer-Integrated Manufacturing* 40 (2016): 1–13, https://doi.org/10.1016/j.rcim.2015.12.007.

25. Y. J. Zhang, N. Huang, R. G. Radwin, Z. Wang, and J. Li, "Flow Time in a Human-Robot Collaborative Assembly Process: Performance Evaluation, System Properties, and a Case Study," *IISE Transactions* 54 (2022): 1–13, https://doi.org/10.1080/24725854.2021.1907489.

26. M. Peshkin and J. E. Colgate, "Cobots," *Industrial Robot: An International Journal* 26, no. 5 (1999): 335–341, https://doi.org/10.1108/01439919910283722.

27. Y. Tao, H. Gao, D. Tan, et al., "An Adaptive Whole-Body Control Approach for Dynamic Obstacle Avoidance of Mobile Manipulators for Human-Centric Smart Manufacturing," *IET Collaborative Intelligent Manufacturing* 7, no. 1 (2025): e70031, https://doi.org/10.1049/cim2.70031.

28. M. Dahl, K. Bengtsson, and P. Falkman, "Application of the Sequence Planner Control Framework to an Intelligent Automation System With a Focus on Error Handling," *Machines* 9, no. 3 (2021): 59, https://doi.org/10.3390/machines9030059.

29. M. Dalle Mura and G. Dini, "Designing Assembly Lines With Humans and Collaborative Robots: A Genetic Approach," *CIRP Annals* 68, no. 1 (2019): 1–4, https://doi.org/10.1016/j.cirp.2019.04.006.