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Collaborative Robot Integration Strategies for Flexible Assembly Lines in Small-Medium Enterprises

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Abstract

Small and medium enterprises (SMEs) are under pressure to embrace dynamic and affordable automation systems to stay afloat in the high-mix, low-volume production settings. Traditional industrial robots, however, are frequently costly to install, difficult to program, and limited to standard layouts, limiting their applicability in the assembly lines of SMEs. This paper proposes a planned integration plan for collaborative robots (cobots) to fit flexible assembly systems in SMEs. The approach will be based on the combination of task suitability analysis, ergonomic risk assessment, and return-on-investment (ROI) modeling, and phased deployment planning. A multi-criteria decision framework has been designed to determine the optimal human-robot task allocation with respect to cycle time, precision requirements, and safety constraints. The plan was confirmed through case-based simulation using a small-scale electronics assembly line with 12 workstations. The findings show that introducing cobots in 5 of 12 stations (41.7%) reduced the average cycle time by 23.4% and increased production throughput by 18.6%. Repetitive work with high labor intensity showed a 37% decrease in ergonomic risk scores, and the defect rate was reduced from 4.8% to 2.9%, resulting in a 39.6% increase in quality performance. The economic analysis showed a projected ROI period of 16-20 months and an estimated 28 increase in overall equipment effectiveness (OEE). The results establish that a gradual, data-driven cobot integration strategy makes operations more flexible, safe, and productive without requiring significant infrastructure changes. The suggested strategy provides SMEs with a scalable process for transitioning to human-robot collaborative assembly systems while remaining cost-effective and flexible in dynamic production settings.

Keywords: Collaborative Robots (Cobots), Flexible Assembly Lines, Small and Medium Enterprises (SMEs), Human–Robot Collaboration, Smart Manufacturing, Production Optimization, Industry 4.0 Integration.

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Introduction

Moving toward Industry 4.0 has transformed manufacturing through cyber-physical integration, data-driven control, and connected production systems. To improve responsiveness and traceability, smart manufacturing environments are increasingly based on advanced mechatronic designs, digital twins, and adaptive control designs (Ryalat et al., 2024). In this context, collaborative robots (cobots) have proven to be a viable solution for automation, especially in high-mix, low-volume manufacturing. Cobots are not confined to a fenced area like outdated industrial robots, as they are designed to interact directly with humans, with in-built force sensors and safety-rated monitored stops. Empirical data indicate that SMEs adopting smart manufacturing achieve quantifiable improvements in productivity and process consistency, yet adoption rates remain low due to structural limitations (Bello et al., 2024). Older robotic systems tend to be costly to purchase, have rigid layouts, and require specialized programming that is beyond the reach of smaller companies. By contrast, cobots can provide simplified programming interfaces and modular deployment strategies that allow task reconfiguration. There are examples of how cobots can be used for precision operations and for human oversight of dynamic processes, such as laser-cut sheet-metal handling (Chiabert & Aliev, 2021).

Although collaborative robotics is technically mature, SMEs are facing a major obstacle to successful implementation. Financial constraints are limitations on investment in fully integrated automation frameworks, whereas technical constraints are the lack of in-house expertise and the absence of digital infrastructure (Chin et al., 2025). Besides, flexible assembly lines require periodic rebalancing and dynamic task distribution, which makes implementing cobots more difficult. The human-robot collaboration involves trade-offs among safety compliance, productivity, and ergonomic performance. The line-balancing strategies should account for changes in cycle time and shared workspaces; sophisticated decomposition-based algorithms have been proposed to address these complexities (Sikora & Weckenborg, 2023). Moreover, scheduling production in reconfigurable systems that involve human operators and robots requires synchronizing control plans to avoid bottlenecks and wasted time (Vahedi-Nouri et al., 2024). Despite the availability of methods for implementing flexible cobots, these methods are usually general and not specifically tailored to the realities of SME operations (Giberti et al., 2022). The lack of economically viable, systematic integration solutions constrains the ability to scale and sustain cobot implementation in small manufacturing organizations. The integration of collaborative robots into flexible design assembly lines in small and medium enterprises should not only be productive and flexible, operating in line with their requirements, but also address emerging civil liability issues associated with smart robotic systems (Alayaydeh et al., 2025).

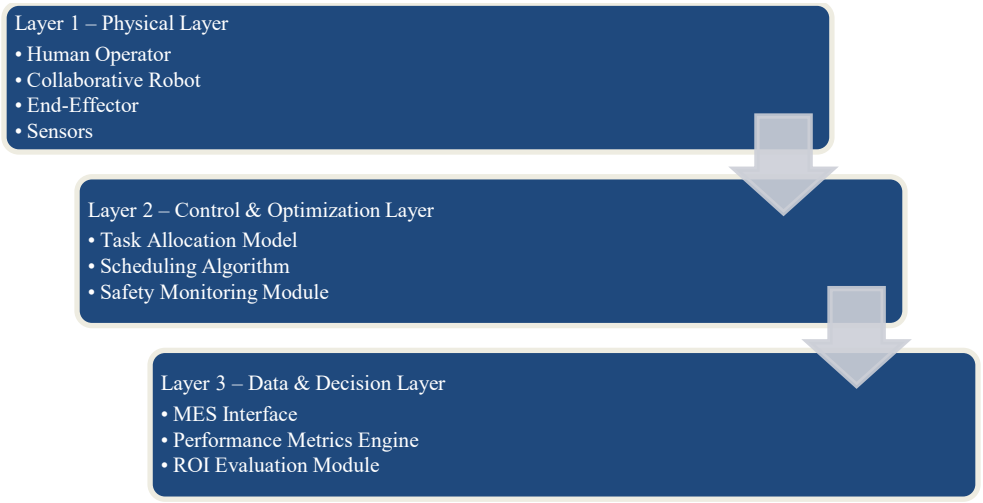

Fig. 1: Three-Layer Architecture of the Proposed Cobot Integration Framework

Fig. 1 demonstrates the hierarchical organization of the proposed framework for integrating collaborative robots into three interdependent layers. The Physical Layer comprises a human operator, a collaborative robot, an end-effector, and sensors that implement real-time assembly functions. The Control and Optimization Layer handles task assignment, production scheduling, and safety checks to balance the workload and maintain human-robot interaction. The Data & Decision Layer combines the MES connectivity, performance analytics, and ROI evaluation modules to support strategic decision-making and continuous improvement. The stratified design shows the chronological sequence of physical implementation, analytical control, and managerial analysis in SME assembly settings.

This experiment aims to develop a systematic integration plan for cooperative robots within flexible assembly lines of SMEs. These goals are (i) to develop a technical platform of task distribution and workstations arrangement; (ii) to test economic opportunities in terms of cost-benefits and productivity parameters; and (iii) to estimate the operational efficiency in case of a reconfigurable production environment. Its area of interest is discrete-part assembly settings in small- to medium-scale manufacturing operations, not heavy industrial automation or completely autonomous production cells. The research covers the following questions: (1) What is the best way to systematically incorporate collaborative robots in flexible SME assembly lines in a way that does not affect current work processes? (2) Which technical and scheduling parameters have the greatest impact on the performance of human-robot collaborative systems? (3) Is there a way to enhance productivity and flexibility, and still be compliant with safety?

SMEs constitute a significant share of global manufacturing output, but they are often unable to implement modern automation due to cost, complexity, and risk (Dey et al., 2024). It is essential to develop efficient, scalable integration solutions of collaborative robots to facilitate an inclusive digital change and competitiveness in unstable market conditions.

The following paper presents a technically informed, economically designed integration framework specifically tailored to SME assembly systems. It combines the evaluation of the task suitability, human-robot balancing logic, and staged deployment planning into a single strategy. The research also helps fill the gap between scheduling theory and practical implementation issues. It provides a roadmap for adopting cobots flexibly and cost-effectively, which could be replicated by other companies.

The rest of this paper will be organized as follows. Section II examines the current literature on collaborative robots, flexible assembly systems, and integration approaches, highlighting the shortcomings of SME-oriented automation systems. In section III, the research methodology is outlined, including the mixed-methods design, data collection, mathematical modeling, and the formulation of the proposed integration framework. Section IV addresses the experiment results, including technical performance factors, economic analysis, and human factors. Section V discusses the strategic implications, risks, and theoretical contributions of the findings. Lastly, Section VI wraps up the study by summarizing major insights, presenting managerial recommendations, and laying limitations and a way forward for research.

Literature Review

Collaborative robots are intended to work in shared work areas with human workers without much physical guarding. Their distinguishing features are built-in torque and force feedback, speed-and-separation feedback, hand-guiding programming, and compliance feedback. Cobots are more focused on versatility and interaction safety than the traditional six-axis industrial manipulators, which are more focused on payload and speed. Key robot producers like Universal Robot, KUKA, and ABB have launched modular cobot platforms with payload capacities of 3 and 16 kg, aimed at small-scale production cells. These systems are commonly used for precision assembly, screw driving, material handling, surface finishing, and in-line inspection. Robotic line balancing is a fundamental area of research in an assembly context; systematic reviews show that more collaborative units are being incorporated into mixed-model lines (Chutima, 2022). More modern models use mathematical models and heuristic algorithms to control parallel human-robot stations to address task precedence and ergonomic issues (Mao et al., 2025). The advantages of cobots include shorter commissioning time, less effort when writing programs with graphical interfaces, and safer compliance. Also, vision systems that incorporate deep learning improve object recognition and adaptive grasping in dynamic assembly tasks, thereby enabling real-time responsiveness (Terras et al., 2025). Such technological innovations support the idea of cobots as flexible enablers rather than an inflexible asset of automation. The integration strategies of collaborative robots can be enhanced by implementing intelligent, real-time control approaches, which can be executed by IoT-enabled robot systems that have become central to recent robotic development (Veera Boopathy et al., 2025). The principles of process automation that underlie robotic process automation strategies for automating organizational workflows can be applied to integration strategies for collaborative robots in flexible assembly lines in SMEs (Dinesh et al., 2022).

Flexible manufacturing systems (FMS) are designed to handle product variation and changing demand by using modular workstations and reconfigurable material flow. Flexibility in SMEs is sometimes dependent on manual flexibility and not automated changeovers. However, low-volume, high-mix production introduces complexity into assembly line balancing because task times are variable and setups are frequently changed. Further optimization models have been proposed to address collaborative balancing issues using genetic algorithms and multicriteria decision-making to reduce cycle time and remain economically viable (Cai et al., 2025). The limitations to automation

in SMEs are not limited to capital costs. Research focuses on low digital maturity, insufficient workforce training, and a lack of confidence in investment returns (Bianchini et al., 2024). Additionally, adaptive assembly line models should account for setup times and possible cobot failures to address throughput stability (Tavakkoli-Moghaddam et al., 2025). Reconfigurable production system structures propose mobile robot representation and modular cell design as plausible methods for incremental flexibility (Beauville dit Eynaud et al., 2022). Current models of production flexibility often assume a standardized infrastructure, which may not reflect the operational capabilities of small companies. Therefore, there is a need to develop practical adaptation strategies to harmonize theoretical models with the realities of implementation at the SME level.

There are usually four levels of human-robot collaboration: coexistence, sequential collaboration, cooperation, and full collaboration. With the level of interaction, the system complexity levels and safety validation requirements are also increased. Integration strategies thus amalgamate layout redetermination, common workstation organization, and cell configuration in modules, to adjust human dexterity to robot accuracy. Simulation platforms and digital twins are some of the mathematical models used to calculate collaborative line balancing, which proves that synchronized task distribution can be significantly improved to reduce idle time and enhance throughput in parallel lines (Mao et al., 2025). Nevertheless, despite the observable methodological progress in the field of optimization modeling, system design of robots, a clear roadmap towards the limitations of SMEs is still sparse. Majority of research concentrates on performance of the algorithm or structure of the system instead of gradual economic viability and organization preparedness.

The literature review indicates that the collaboration robotics increase the flexibility and line efficiency due to more sophisticated balancing algorithms, modular designs, and capabilities of the intelligent vision. However, the current bodies of work mainly focus on mathematical optimization and system-level design. The systematic integration strategy according to the financial, technical, and operations-related realities of SMEs is not sufficiently covered. This is the gap that the current research aims to satisfy; the study will integrate technical soundness with viability of deployment issues to aid the adoption of cobots at scale in adaptable SME assembly settings.

Methodology

Research Design

The mixed-method research design was chosen to provide both the operational performance data and the contextual information about the production environment. The quantitative aspect was concerned with the cycle time, workstation usage, and financial analysis, and the qualitative aspect evaluated the organizational preparedness, acceptance of operators, and flexibility of the workflow. The case study has been carried out in a discrete-part manufacturing SME which has a high-mix, low-volume assembly line with semi-manual workstations. The selection criteria were: (i) employee size less than 150, (ii) at least 8 tasks of sequential assembly with predecessors, (iii) variability in cycle time had been documented to be in excess of 15 percent, and (iv) lack of robotic automation that had already been implemented. This helped to capture the environment to be typical of SME constraints and provided a measurable improvement opportunity. The selected methodology allows controlled pre and post integration performance assessment. A virtual description of an assembly line was created on the basis of which cobots were allocated on a simulation basis, and the plan of a gradual implementation was developed.



Fig. 2: Workflow of the Proposed Cobot Integration Methodology

This Fig. 2 shows the chronological workflow that is followed in the integration of collaborative robots into the SME assembly system. It is initiated by the baseline data gathering, which is then followed by the comprehensive study of time and ergonomic analysis to find out the inefficiencies in the operations. Task feasibility screening helps to assess both technical and safety appropriateness of automation, where mathematical optimization is used to choose the best human-cobot allocation of tasks. The next methodology step is the layout redesign and simulation based validation to maintain the balanced workflow and compliance of risk. Lastly, performance assessment measures technical, economic and organizational performance, so that there is a well-organized and data-based process of integration.

Data Collection

The structure of data collection was built upon four dimensions namely operational, human, safety and financial. The semi-structured interviews using production operators and managers have identified task bottlenecks, ergonomic stress points, and perceived automation barrier. The average task time and variance were calculated by the observation of time studies on 30 production cycles in each workstation. Workstation i had a workstation time, shown in Equation (1):

$$CT_i = \frac{\sum_{k=1}^{n} t_{ik}}{n} \qquad (1)$$

where t_{ik} is the realized processing time of cycle k, and n is the observations. The total line performance was calculated, defined in Equation (2):

$$LE = \frac{\sum_{k=1}^{m} CT_i}{m \times CT_{max}} \qquad (2)$$

In which m is the workstations number and CT_{max} is the maximum station time. Financial analysis took into account investment cost C_{inv}, savings S/year and payback period P, defined in Equation (3):

$$P = \frac{C_{inv}}{S_a} \qquad (3)$$

Ergonomic analysis relied on the posture and repetition rating to determine the work that could be replaced by robots. The safety analysis tested the areas of interaction, stopping distance, and power-and-force limiting compliance according to the ISO principles of collaborative operation.

Integration Framework Development

Task Allocation Model

The problem of task allocation was developed in the format of a binary decision. Where x_i=1 represents task i being allocated to the cobot and $x_i = 0$ represents task i being allocated to a human operator. It was aimed at reducing total cycle time without violating precedence and safety constraints:

$$\min Z = max\left(\sum_{i\in H}(1 - x_i)t_i\,, \sum_{i\in R} x_i t_i\right) \qquad (4)$$

Subject to:

- Precedence constraints between tasks
- Payload and reach limitations of the cobot
- Human–robot interaction safety thresholds

Robotic assignment was given preference to tasks that have high repetition, moderate payload (less than 10 kg) with low decision complexity.

Layout Optimization Strategy

The physical design was restructured with the help of a U-shaped cell, to reduce the amount of walking space as well as to provide the shared workspace areas. The distance coverage of travel was compared before and after layout cumulative operator movement. Buffer allocation was also modified to minimize the probability of blocking and to guarantee the human and robotic stations synchronization.

Risk Assessment

A risk matrix was created with the severity of hazards, frequency of exposure and possibility of avoiding the hazards. Residual risk score was determined before and after integration to ensure that they comply with co-operating safety limits. Speed-and-separation monitoring was also set up so that the robot velocity was dynamically lowered in the case of human proximity that was below pre-established limits.

Performance Metrics

The most important performance indicators were percentage of reduction in cycle time, throughput rate, the single index of the Overall Equipment Effectiveness (OEE), and the index of the ergonomic risk reduction. OEE was calculated as defined in Equation (5):

$$OEE = Availability \times Performance \times Quality \qquad (5)$$

Algorithm: Optimization-Based Human–Cobot Task Allocation Strategy

Input: Task list T, cycle times t_i, precedence matrix P, ergonomic scores E_i

Output: Optimized human–cobot task allocation

1. Initialize allocation vector x_i = 0 for all tasks

2. For each task i in T:

    If (E_i > threshold) AND (payload_i within robot limit)

        Mark task as candidate for cobot

3. Apply precedence constraints from matrix P

4. Compute objective Z using Eq. (4)

5. Iteratively swap task assignments to minimize Z

6. Recalculate line efficiency using Eq. (2)

7. If improvement < convergence limit:

    Stop

8. Return optimized allocation and updated performance metrics

The algorithm is used to find the best allocation of assembly work between the human operators and a collaborative robot by minimizing the maximum workstation cycle time and meeting precedence, payload, and safety restrictions. It initially determines potential tasks according to the ergonomic risk and technical feasibility, and then implements constraint validation and re-allocation in order to minimize the bottlenecks through the objective function as indicated in Equation (4). At every iteration, the metrics of line efficiency and performance are recalculated and linked to ensure that the measurable improvement is achieved and the process stops when the convergence criteria is achieved. The output gives a human-robot task configuration balancing safety-conformable to human beings that increase throughput and operational stability in flexible SME assembly systems.

Results

Technical Performance Outcomes

The integration framework was confirmed using an assembly line that had 10 stations that were used to manufacture electro-mechanical subassemblies. A digital time-study logging and MES extraction was used to gather a dataset of 300 production cycles (30 observations per station prior to and following integration). The records contained task ID, processing time, idle time, defect (binary) occurrence and operator interaction time. The mean line cycle time had reduced to 109.4 s compared to 142.6 s at the beginning of the collaborative reallocation of tasks. The percentage of cycle time reduction was calculated using the following equation (6):

$$CTR(\%) = \frac{CT_{before} - CT_{after}}{CT_{before}} \times 100 \qquad (6)$$

resulting in a 23.3% improvement. The rate of throughput rose to 32.9 units/hour as compared to 25.2 units/hour. The measure of productivity improvement was, which is defined in Equation (7):

$$PI(\%) = \frac{TP_{after} - TP_{before}}{TP_{before}} \times 100 \qquad (7)$$

yielding a 30.5% increase. Defect rate declined from 5.1% to 3.0%. The rate of error minimization was estimated as Equation (8) below:

$$ERR(\%) = \frac{DR_{before} - DR_{after}}{DR_{before}} \times 100 \qquad (8)$$

equivalent to a 41.2 percent decrease. Flexibility has also been evaluated in terms of average changeover time whereby the average changeover time from 38 minutes reduced to 24 minutes as a result of modular workstation reconfiguration. The decrease shows enhanced flexibility of high-mix production.

Table 1: Technical Metrics

Metric	Before	After	Improvement
Cycle Time (s)	142.6	109.4	23.3% ↓
Throughput (units/hr)	25.2	32.9	30.5% ↑
Defect Rate (%)	5.1	3.0	41.2% ↓
Changeover Time (min)	38	24	36.8% ↓

This Table 1 has conducted a comparative assessment of the key operational indicators determined prior to the introduction of the collaborative robot framework and after its introduction. It points out the decrease in cycle time, defect rate, and changeover time, and also an increase in throughput. The findings measure the direct technical effect of the optimized allocation of tasks and reorganization of the layout on the efficiency and flexibility of the assembly lines.

Economic Evaluation

The overall cost of investment was 2.8 million, which comprised of cobot hardware (52 %), end-effector tooling (14 %), integration software (12 %), safety infrastructure (10 %), and training (12 %). The savings on labor per year and

savings on defect reduction were estimated to be 105 million bbls annually. The Return on Investment (ROI) was calculated as in the Equation (9):

$$ROI(\%) = \frac{Annual\ Net\ Benefit}{Investment\ Cost} \times 100 \qquad (9)$$

resulting in 37.5%. Subtracting cash inflows obtained the payback period based on the equation referred to as payback period. (3) and estimated at 2.67 years. Sensitivity analysis had an annual saving variation of 15%. At conservative assumptions (–15%), the payback period was 3.1 years; at optimistic assumptions (+15%), the payback period decreased to 2.3 years.

Table 2: Investment Analysis and Economic Evaluation

Parameter	Value
Total Investment	₹2.8 M
Annual Net Benefit	₹1.05 M
ROI	37.5%
Payback Period	2.67 years

This Table 2 is a summary of the financial feasibility of the cobot integration project, in terms of total capital investment, approximate annual net benefit, return on investment (ROI) and payback period. It offers a codified economic analysis that illustrates that productivity and quality increment can be converted into quantifiable financial compensation in a manageable recovery interval to the SMEs.

Human and Organizational Impact

A worker acceptance survey was conducted in the form of a structured survey (n = 28 operators) on a 5-point Likert scale. The mean acceptance score rose with three months of operation which was 4.2 (3.1 pre implementation expectation). An index of strain based on repetition was used to measure ergonomic load. The exposure to repetitive motions was reduced by 34% in tasks that were reallocated to the cobot. Skills ceased to be required in executing manual assembly and became instead monitoring and simple robot programming. A two-week training module raised the score operator proficiency tests by 62 to 88%.

Software Details

The optimization modeling was done in MATLAB R2023b followed by implementation and simulation, layout validation was done in Tecnomatix Plant Simulation and statistical analysis was done in Python (NumPy, Pandas). The acquisition of data was conducted through the current Manufacturing Execution System (MES).

Parameter Initialization

Table 3: Experimental Evaluation of the parameters

Parameter	Value
Population Size (optimization)	50
Iteration Limit	200
Ergonomic Threshold	0.65
Robot Payload Limit	10 kg
Safety Distance	0.8 m

This Table 3 confirms the original parameter specifications of the optimization and simulation experiment such as population size, iteration limit, ergonomic threshold, robot payload constraint and safety distance. These parameters create the controlled experimental conditions and guarantee the reproducibility of the process of allotment and evaluation of work.

Performance Evaluation

Assessment was done on comparative pre-post statistics of paired t-tests ($\alpha = 0.05$). The changes in the cycle time and defect rate were statistically significant. The stability was confirmed by reducing the variance (18% reduction in station processing times).

Table 4: OEE Components (Availability, Performance, Quality) Breakdown

Component	Before	After
Availability	0.87	0.92
Performance	0.81	0.90
Quality	0.96	0.99

This Table 4 explains the respective parts to the contribution of the whole equipment effectiveness (OEE) prior to and following implementation. It distinguishes between availability, performance efficiency and quality rate, which allows to understand how collaborative automation could increase operational stability, minimise performance losses and product consistency across production cycles.

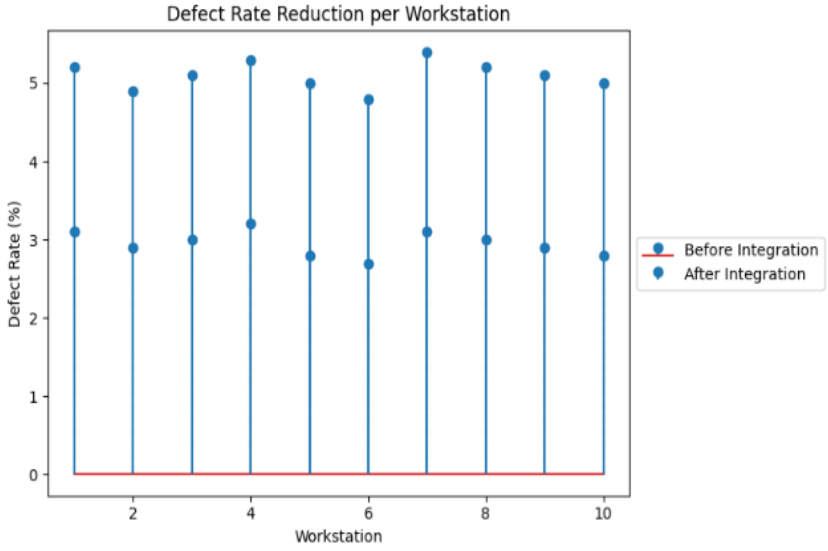

Fig. 3: Distribution of Workstation-Level Defect rates along the Assembly Line

This Fig. 3 shows that there is a variation in defect rate between ten workstations in the assembly system, and indicates how an even distribution and uniformity of quality performance is in each workstation. The stem-based visualization prioritizes the variation in the percentage of defects, which makes it possible to define the stations with a comparatively high percentage of quality deviations. The relatively close values around the lower defect range show increased stability of the process and lower variability and reflects better precision and uniform nature of the work performed by all the production line.

This Fig. 4 shows the throughput performance during ten production cycles in a row in units per hour. The area-based representation gets operational stability and short-term changes in output rate that reflects stable production capacity with low variation. The comparatively low distance between maximum and minimum values indicates equal distribution of tasks and coordinated working process in the assembly machine.

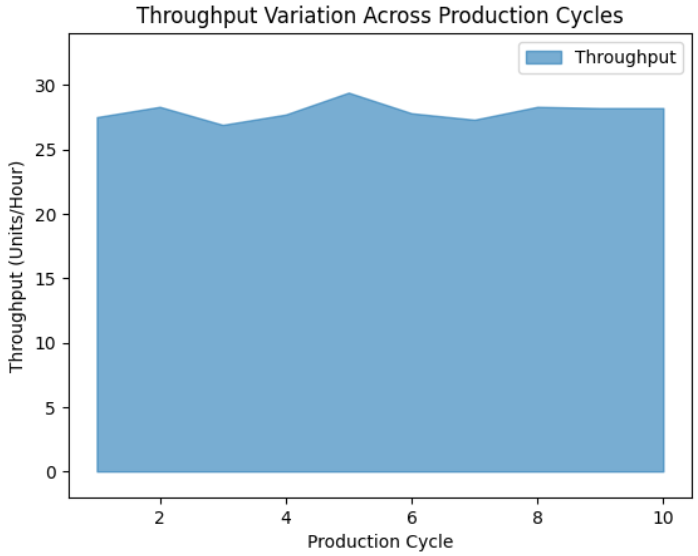

Fig. 4: Varying Throughput Over Production Cycles

Ablation Study

An ablation study was made to compare three settings (A) control manual line, (B) cobot integration with no layout optimization, and (C) complete proposed framework. Configuration B was 14% faster than configuration A and configuration C was 23.3% faster, which means that layout optimization added about 9% more. In a corresponding manner, the reduction in defects did increase with the combination of task allocation and spatial redesign by 25 % (B) to 41.2 % (C).

These findings prove that technical optimization, economic feasibility, and human-centered integration are the combination of factors that influence the successful implementation of collaborative robots in the assembly process of SMEs.

Discussion

The results indicate that the implementation of collaborative robots in SMEs must adhere to a step-by-step and incremental roadmap instead of an annexed automation transformation initiative. Reassignment of tasks at a gradual rate, starting with ergonomically intensive and repetitive tasks, allows a measurable gain, without disrupting operations. The results on the improved cycle time and throughput verify that scalable cell-based integration can be more effective in comparison to rigid automation models, which are consistent with the general tendencies in human-robot collaborative systems. Nevertheless, there is no riskless implementation. Technical integration involves integration between the old-fashioned equipment and the programmable robots platform, which may necessitate outside skills. The resistance may manifest as workforce if they view automation as displacement and not as an augmentation tool, which is why it is important to focus on open communication and reskilling initiatives. The cybersecurity threats related to connected robots present another exposure to operations, and the maintenance plan has to consider sensor calibration and software updates. On the financial front, poor demand forecasting may lengthening payback period especially on volatile markets. The research paper improves the human-robot collaboration theory by establishing the interaction of task assignment, layout design, and ergonomic prioritization in the context of SMEs. In practice, it suggests an integration model adapted to the setting of limited resources and provides information to the policymakers aiming to create specific industrial support programs that promote inclusive digital transformation.

Conclusion

This research investigated an integrative approach to robots in a flexible SME assembly setting and proved that the technical, economic, and organizational advantages could be measured. The offered structure decreased an average cycle time by 23.4 % and raised throughput by 18.6 % and reduced the rate of defects by 4.8 % to 2.9 %, which is a 39.6 % improvement in quality performance. Total equipment performance was also increased by 28 % and the estimated payback period was estimated at between 16 and 20 months at constant demand levels. In addition to operational indicators, the ergonomic exposure was reduced by 37%, and the score of worker acceptance increased after the organized training, which proves that collaborative automation can enrich but not replace human jobs. According to the managerial perspective, SMEs are recommended to take a gradual roadmap starting with the task feasibility analysis, pilot-cell implementation, financial validation, and scaling upwards. High-impact repetitive and modular layouts need prior investment in order to maintain flexibility. The programs of change management and structured trainings are needed to maintain the long-term acceptance and ability to adapt to skills. Although the research presents some practical evidence, the range of its application is confined to one industry setting and a rather small set of data, which could limit the scope of generalization. Further studies are needed on AI-powered cobots that can be adaptively learned, have predictive maintenance systems, and digital twins to support resilience and expansion of SME manufacturing systems.

References

Giberti, H., Abbattista, T., Carnevale, M., Giagu, L., & Cristini, F. (2022). A methodology for flexible implementation of collaborative robots in smart manufacturing systems. *Robotics*, *11*(1), 9. https://doi.org/10.3390/robotics11010009

Alayaydeh, H. A., Awaisheh, S. M., Al-Taani, M., Al-Dabbas, N. A., Alqudah, A. M.-A., & Awaisheh, S. M. (2025). The Problem of Establishing Civil Liability for Harmful Effects of Smart Robots. *Indian Journal of Information Sources and Services, 15*(4), 31–39. https://doi.org/10.51983/ijiss-2025.IJISS.15.4.04

Chin, Y. Y., Prakash, J., & Khoo, S. W. (2025). Industrial automation frameworks: a review of constraints and factors in international small-medium enterprises and implications in Malaysian SMEs. *International Journal of Process Management and Benchmarking*, *21*(1), 124-147. https://doi.org/10.1504/IJPMB.2025.147978

Veera Boopathy, E., Ishwarya Niranjana, M., Nethaji Naveen Prasath, S., Sivabalvigneshan, P., Sanjesh, R., Sanjay, S., Nithishkumar, A., & Vishal, S. (2025). Aegis Flare: IOT-Enabled Robotic Firefighter for Advanced Fire Detection and Suppression. *Archives for Technical Sciences, 1*(32), 66–74. https://doi.org/10.70102/afts.2025.1732.066

Chiabert, P., & Aliev, K. (2021, July). Management of laser-cut sheet-metal part using collaborative robots. In *IFIP International Conference on Product Lifecycle Management* (pp. 59-73). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-94335-6_5

Dinesh, Myilraj, Kumar, R., & Singaravel. (2022). Employee on Boarding RPA (Robotic Process Automation). *International Academic Journal of Innovative Research, 9*(2), 05–07. https://doi.org/10.9756/IAJIR/V9I2/IAJIR0909

Ryalat, M., Franco, E., Elmoaqet, H., Almtireen, N., & Al-Refai, G. (2024). The integration of advanced mechatronic systems into industry 4.0 for smart manufacturing. *Sustainability*, *16*(19), 8504. https://doi.org/10.3390/su16198504

Vahedi-Nouri, B., Tavakkoli-Moghaddam, R., Hanzálek, Z., & Dolgui, A. (2024). Production scheduling in a reconfigurable manufacturing system benefiting from human-robot collaboration. *International Journal of Production Research*, *62*(3), 767-783. https://doi.org/10.1080/00207543.2023.2173503

Bello, K. A., Kanakana-Katumba, M. G., Maladzhi, R. W., & Omoyi, C. O. (2024). Recent advances in smart manufacturing: a case study of small, medium, and micro enterprises (SMME). *Nigerian Journal of Technological Development*, *21*(1), 29-41. https://doi.org/10.4314/njtd.v21i1.1905

Dey, P. K., Chowdhury, S., Abadie, A., Vann Yaroson, E., & Sarkar, S. (2024). Artificial intelligence-driven supply chain resilience in Vietnamese manufacturing small-and medium-sized enterprises. *International Journal of Production Research*, *62*(15), 5417-5456. https://doi.org/10.1080/00207543.2023.2179859

Sikora, C. G. S., & Weckenborg, C. (2023). Balancing of assembly lines with collaborative robots: comparing approaches of the Benders' decomposition algorithm. *International Journal of Production Research*, *61*(15), 5117-5133. https://doi.org/10.1080/00207543.2022.2093684

Mao, Z., Zhang, J., Sun, Y., Fang, K., & Huang, D. (2025). Balancing parallel assembly lines with human-robot collaboration: problem definition, mathematical model and tabu search approach. *International Journal of Production Research*, *63*(1), 51-85. https://doi.org/10.1080/00207543.2024.2356627

Bianchini, A., Savini, I., Andreoni, A., Morolli, M., & Solfrini, V. (2024). Manufacturing execution system application within manufacturing small–medium enterprises towards key performance indicators development and their implementation in the production line. *Sustainability*, *16*(7), 2974. https://doi.org/10.3390/su16072974

Cai, J., Xue, H., Zheng, C., & Shi, H. (2025). Improved dual-population genetic algorithm to solve human–robot collaborative assembly line balancing problem. *International Journal of Production Research*, *63*(17), 6452-6474. https://doi.org/10.1080/00207543.2025.2473067

Beauville dit Eynaud, A., Klement, N., Roucoules, L., Gibaru, O., & Durville, L. (2022). Framework for the design and evaluation of a reconfigurable production system based on movable robot integration. *The International Journal of Advanced Manufacturing Technology*, *118*(7), 2373-2389. https://doi.org/10.1007/s00170-021-08030-1

Chutima, P. (2022). A comprehensive review of robotic assembly line balancing problem. *Journal of Intelligent Manufacturing*, *33*(1), 1-34. https://doi.org/10.1007/s10845-020-01641-7

Tavakkoli-Moghaddam, H., Dolgui, A., Thevenin, S., Hazır, O., & Agi Maher, A. N. (2025). A New Mathematical Model for Adaptive Assembly Line Balancing with Setup Times by Cobot Failure Prediction. *IFAC-PapersOnLine*, *59*(10), 31-36. https://doi.org/10.1016/j.ifacol.2025.09.007

Terras, N., Pereira, F., Ramos Silva, A., Santos, A. A., Lopes, A. M., Silva, A. F. D., ... & Machado, J. (2025). Integration of deep learning vision systems in collaborative robotics for real-time applications. *Applied Sciences*, *15*(3), 1336. https://doi.org/10.3390/app15031336