LOW-COST MODULAR COLLABORATIVE ROBOT INTEGRATION: IMPROVING PROCESS LINE EFFICIENCY IN CONNECTOR PRODUCTS

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ABSTRACT

Operational inefficiencies in a high-mix, low-volume manufacturing environments often result in line imbalances and extended assembly times, thereby reducing productivity. At Pricon Microelectronics, Inc. (PMI), multiple product lines consistently operated below the expected line balance threshold of 85%, a level considered essential for achieving optimal utilization and sustaining efficient production flow. This condition was primarily attributed to the reliance on manual operations. To address this, A DMAIC methodology was employed as a structured problem-solving approach. Using this framework, cost-effective collaborative robots were integrated into existing manual workstations. This implementation led to operation performance gains between 87.58% to 100% and a manpower cost from initial range of $36,735 - $31,487 to narrow range of $31,487 - $5,247 yielding annual savings of $41,982. The integration of cobot provided an effective integration with existing workflows, significantly improving line balance and overall process efficiency.

1.0 INTRODUCTION

Pricon Microelectronics Inc. (PMI), a global leader in the connectors product line, faces challenges in meeting rising demand due to its reliance on manual-intensive processes that sustain operations at a break-even level, but without enabling significant improvements in performance efficiencies. While product quality remains a benchmark, sustaining competitiveness requires modernizing not only the product but also the production process. This highlights the internal need for process improvement to maintain optimal output and meet market expectations.

Efforts to improve operational efficiency included layout optimization with a 1-meter walkway between workstations to reduce movement and support flow. Workload balancing and batch handling adjustments were also applied, but the results fell short of the company's line balance standard.

Following a performance metrics and a set of requirement criteria PMI automation specialists proposed to integrate and deployed a Modular Collaborative Robot (cobot). This integration effectively aimed to improve line efficiency and improve task allocation in different product line.

Fig. 1. Low-Cost Mobile Cobot Platform (LC-MCP)

The cobot used in this study offers a cost-effective automation solution at approximately $4,000, including both the robot and development costs. This is significantly lower than traditional industrial robots or SCARA units, which typically range from $8,000 to $30,000, excluding integration. Its design allows seamless integration into existing lines without major modifications. With user-friendly programming and compatibility with both manual and semi-automated environments, it performs various pick-and-place tasks, adapts to product changes, and supports dynamic production demands. This flexibility makes it well-suited for improving throughput in high-mix, low-volume manufacturing.

2.0 REVIEW OF RELATED WORK

An investigative study on cobots showed that improving line balance from 40.33% to 85.12% increased productivity by 138% and reduced manpower from 11 to 9 through cobot-assisted loading and task redistribution, such as combining rivet-handle insertion and packing-stacking. [1].

3.0 METHODOLOGY

This study adopted the DMAIC methodology as a structured approach to improve process efficiency, given its effectiveness in achieving measurable and sustainable results in manufacturing.

3.1 Define Phase

3.1.1 Business Case

The current connector assembly setup relies heavily on manual operations, offering limited scalability and showing no significant impact on production improvement. Conventional machines add to this challenge, as they are often inflexible and costly to adapt for high mix, low volume environments.

3.1.2 Problem Statement

Figure below illustrates the line balance performance across different production lines, represented as a bar graph.

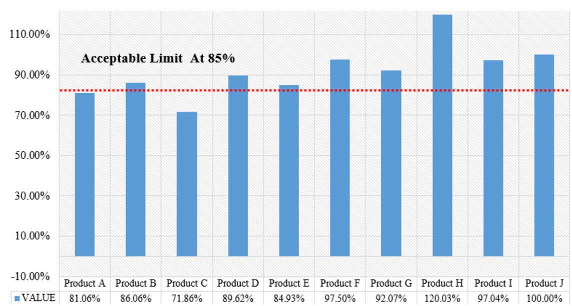


Fig. 2. Line balance of 10 different line in relation to their limit threshold.

Fig. 2 highlights the efficiency and workload distribution among various stages or workstations in the assembly or production process.

Despite the implementation of layout optimization, workload balancing, and batch handling adjustment across three product lines (A, C, and E) failed to meet the company's 85 percent line balance threshold, while Products B and D only slightly exceeded it. Manual-intensive operations continue to impact workflow efficiency and labor costs, limiting overall process performance and profitability.

3.1.3 Objective Statement

This project aims to improve the operational performance of the connectors process for Products A (81.06%), B (86.06%), C (71.86%), D (89.62%), and E (84.93%) through the deployment of modular cobots. Each product follows a different deployment schedule, to be accomplished by the end of February 2025. The goal is to achieve a process efficiency increase of 85% to 98% across all products.

3.1.4 Scope

This project evaluated the impact of modular cobot integration on process efficiency. Five of ten product lines were selected based on process efficiency, with Product D serving as a benchmark for assessing automation effects on an already optimized line.

3.2 Measure Phase

3.2.1 General Process Flow

This section presents the general workflow diagram for connectors product lines.

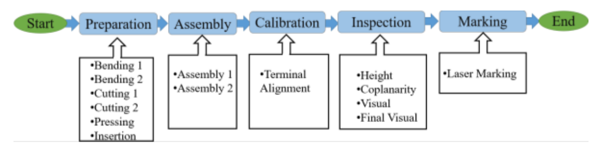


Fig. 3. Macro-Process of Product Lines (A-E)

Fig. 3 illustrates the general step-by-step workflow for the five product lines and their respective process stages. Although conventional machines are present, they are designed for specific tasks and the overall workflow remains dependent on manual labor. Additionally, the process stages vary across products, reflecting differences in design requirements and assembly complexity.

3.2.2 Data Collection

Relevant data were acquired from existing operational records and technical resources that reflect the state of operations prior to the integration of cobot. The data collection focused on gathering key information such as line balance.

Table 1. AAT and Line Balance Across Product Lines

Category		Product A		Product B		Product C		Product D		Product E	
		AAT (s)	Manpower	AAT (s)	Manpower	AAT (s)	Manpower	AAT (s)	Manpower	AAT (s)	Manpower
Preparation	Bending 1	4.43	1	-	-	-	-	-	-	7.76	1
	Bending 2			-	-	-	-	-	-		
	Cutting 1	-	-	-	-	-	-	-	-	6.2	1
	Cutting 2	-	-	-	-	-	-	-	-		
	Pressing	-	-	-	-	4.09	1	-	-		
	Insertion	-	-	5.1	1	3.12		5.88	1	4.09	2
Assembly	Assembly 1	8.12	1	13.49	3	5.85	1	-	-	12.62	
	Assembly 2	8.52	1	-	-	9.79	2	-	-		
Calibration	Terminal Alignment	4.95	1	2.86	1	-	-	-	-	-	
Inspection	Height	7.98		5.22		8.64	1	5.86	1	6.9	
	Coplanarity	8.35	1	5.08	1	7.5	1	6.99	1	8.16	1
	Visual	7.37	1	5.75	1	5.83	1	-	-	6.84	1
	Final Visual	-	-	3.12		-		-	-	-	-
Marking	Laser Marking	3.57	1	4.45		-		-	-	-	-
Total		**53.29**	**7**	**45.07**	**7**	**44.82**	**7**	**18.73**	**3**	**52.57**	**6**
Line Balance		**81.06%**		**86.06%**		**71.86%**		**89.32%**		**84.93%**	
# of semiautomation		**4**		**6**		**3**		**1**		**6**	

Table 1 presents the number of semi-automated operations, actual assembly time (AAT), manpower allocation, and line balance across process phases for five products. The number of semi-automations implemented varies depending on the specific product and phase. Inter-machine activities remain manual indicating targeted effort to improve it to full automation. Process configurations also differ among products.

3.3 Analysis Phase

Analyzing the potential cause for the low operational performance of the Connectors product line, a Fishbone analysis was conducted to determine whether the cause is incurred by which aspect.

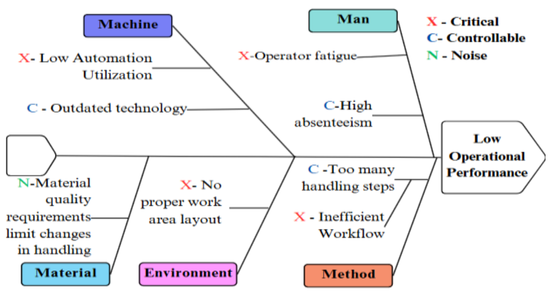


Fig. 4. Fishbone diagram for potential root causes of low operational performance of connectors product line.

To validate and find the root cause of the problem from the discoveries from the Fig. 4, a Why-Why Analysis was conducted. While material was recognized as a critical quality requirement, the decision was made to exclude it from root cause analysis due to its limited relevance to the problem.

Table 2. Why-Why Analysis for operational performance

CATEGORIES	PROBLEM	WHY 1	WHY 2	WHY 3	WHY 4
MAN	Operator Fatigue	It's a Manual Intensive Process	Process rely heavily on manual labor	Perform Repetitive handling	-
MACHINE	Low Automation Utilization	Requires manual feeding	No Integrated pick and place system	Design is only for manual operation	Existing machine configuration is optional
METHOD	Inefficient Workflow	Inconsistency in manual process	Many unnecessary movement	Process relies to manual handling for repetitive pick and place	No automation implemented for material transfer
ENVIRONMENT	No proper work area layout	Arrangement doesn't efficient flow	Workspace not optimize for process requirement	Ergonomics was consider in work area design	Physical space is limited

Table 2 shows that across the multiple branches, specifically man, machine, method, and environment, the root cause consistently traced back to the reliance on the process being manual-intensive. This dependency results in operational performance inefficiencies such as prolonged activity times and imbalance workflows.

3.3.1 Root Cause Validation

To validate the root cause from the why-why analysis, an assessment was conducted using collected data from the 5 product lines. Table 3 summarizes the relation of the process from the existing data to the problem. Its operational inefficiencies are consistently linked to manual dependencies across all categories.

Table 3. Validation of Root Causes Affecting Operational Performance

Root Cause	Validation Method	Confirmation Strength
MAN: Manual-Intensive Process	Correlation analysis and Line Balance comparison	**High** – Repetitive pick-and-place operations consume the most time
MACHINE: Existing machine configuration is conventional	Comparative performance and machine configuration analysis	**Very High** - Semi-automation still needs manual input, creating inefficiencies
METHOD: Manual pick-and-place tasks at repetitive stages causing bottlenecks	Bottleneck Analysis using assembly time per product	**High** – Repetitive pick-and-place operations consume the most time
ENVIRONMENT:Congested workspace due to excessive manual handling	Root cause reasoning using operator density and Line Balance	**Moderate** – 1-meter walkway was measured to provide direct confirmation of environmental condition

For man, all product lines A, B, and C are staffed with seven operators each. However, line balance for Product A (81.06%), Product C (71.86%), and Product D (84.94%) falls below the company's 85% acceptable threshold. This suggests high manual involvement is limiting process efficiency despite consistent manpower.

The root cause related to machine was validated by evaluating performance under similar manpower and semi-automated configurations, which all involving manual feeding.

For method, bottleneck analysis in manual pick-and-place tasks, notably during Product C's inspection (8.64s) and Product B's assembly (13.49s).

For the environmental factor, a consistent 1-meter walkway separates the rows of work tables. Despite this spacing, the high operator density in Product Lines A and C with line balance below the threshold indicates potential workspace congestion.

These findings validate the need for targeted interventions, particularly integrating a pick-and-place system between process to improve line balance.

3.4 Improvement Phase

Despite the efforts to optimize the operational performance by redesigning the process layout, the line balance remains below the acceptable threshold.

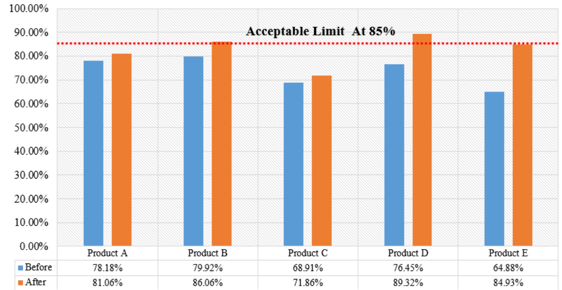


Fig. 5. Line balance performance of five different products before and after layout optimization

Fig 5. illustrates the line balance for Product A to Product E. The chart uses red dot line to indicate the 85% acceptable threshold limit in the company. Despite process layout optimization only Product D with 89.32% improvement and Product B with 86.06% narrowly surpass the 85% benchmark. The results indicates that it is proven insufficient in achieving significant performance gain across all lines.

3.4.1 Proposed Solution

To improve process efficiency PMI automation specialists proposed the integration of cobots to automate repetitive handling tasks. This solution is expected to process efficiency by minimizing variability in repetitive operations.

3.4.2 Automation Criteria and Evaluation

The Analytic Hierarchy Process (AHP) technique is a structured multi-criteria decision-making (MCDM) method used to determine the most suitable robot for deployment based on defined priorities. Priority weights were assigned to each evaluation criterion using AHP, highlighting the relative importance of each factor [2]. Using AHP, these weighted priorities are presented in Fig. 11 to support the evaluation and selection of the appropriate robot model for implementation.

Table 3. Evaluated Robots and key specifications

Brand	Robot Type	Axis	Payload Capacity (kg)	Repeatability (mm)	Reach (mm)	Weight (kg)	Cost
Brand W	Industrial Robot	6	4	±0.02	717	4	$28,000
Brand X	SCARA	4	10	±0.02 (J1+J2), ±0.01 (Z), 0.005 (T)	700	56	$8,876
Brand Y	COBOT	4	0.75	±0.05	440	8	$2,890
Brand Z	COBOT	6	3	±0.03	500	11	$2,600

Table 3 presents the specification of robots evaluated for their potential integration into assembly process. The selection criteria focused on technical parameters that directly affect suitability for material handling tasks where consistent placement directly impacts consistency.

Table 4. Robot Evaluation Summary

Criteria	Priority Weight	Brands			
		W	X	Y	Z
Payload	3.43%	4	3	2	3
Reach	14.03%	5	4	2	4
Repeatability	3.43%	5	4	3	4
Axis	7.36%	5	3	3	5
Ease of Integration	25.5%	3	4	5	4
Cost	46.25%	2	4	5	3
Score		**3.07**	**3.89**	**4.26**	**3.44**

Table 4 shows that among the robots evaluated, Brand Y scored the highest. Even though it has smaller payload, it's cost and ease of integration outweighed the higher specifications of other brands. The capabilities of Brand Y are already sufficient enough to reliably automate repetitive manual tasks.

3.4.3 Integration of Cobots on Product Lines

PMI Automation specialists developed two cobot deployment types for production flexibility: a fixed unit and a mobile unit. Both feature modular designs with customizable end-effectors. The mobile cobot, mounted on a compact wheeled base, enables fast redeployment, quicker setup, and reduced downtime in confined spaces.

It also supports transitions between fully and semi-automated modes and can be reassigned to other lines when needed, enhancing utilization and resource efficiency. The fixed unit provides stable, continuous operation at dedicated workstations.

3.4.3.1 Control System Integration

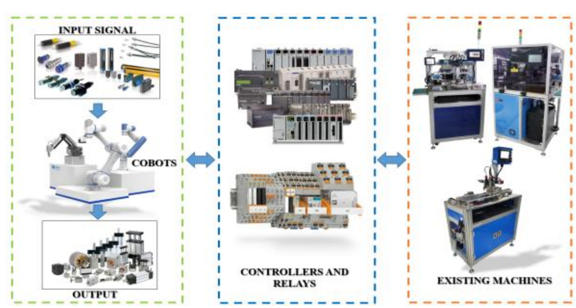


Fig. 6. Process flow on how the robot interfaces with the PLC using digital I/O and relays for control and feedback.

Fig. 6 illustrates the communication interface between the cobot and the Programmable Logic Controller (PLC) implemented through relay-based I/O.
The robot's internal controller executes pre-configured tasks and motion sequences, with real-time adjustments made by sensor input. Relays act as the central logic unit coordinating signals between the robot, conveyors, safety interlocks, peripheral actuators and existing machine.

3.4.3.2 End-Effector Key Specification

Brand Y supports a range of modular end-effectors mounted on a standardized ISO 9409-1-50-4-M3 flange.

Table 4. End-Effector compatibility and Interface Overview

End-Effector	Power Type	Sensor Feedback	Average Swap Time
Pneumatic Gripper	Pneumatic	Magnetic reed switch	2–3 minutes
Vacuum Suction Cup	Pneumatic	Flow sensor	2–3 minutes

Table 4 shows the Brand Y's modular end-effectors, including pneumatic grippers with reed switches for grip detection and vacuum cups with flow sensors for suction monitoring. Both use pneumatic power and standardized flanges for quick tool changes. Given product weights of 5 to 20 grams, precision and gentle gripping are essential.

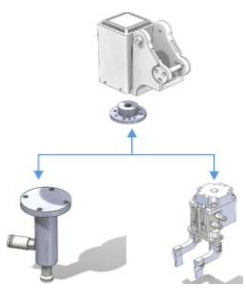


Fig. 7. Example of end-effectors used (Two-finger gripper (right) and Vacuum (left)

Fig. 7 shows two sample end effectors compatible with the cobot. Both use pneumatic interface and toolhead compatibility for rapid swapping

3.4.3.3 Mobile Cobot Key Specifications

The Brand Y is mounted on a mobile platform with a compact wheeled base and locking mechanisms for stable operation and easy transport between workstations. Key mobility parameters are summarized in Table 5, highlighting their impact on production line flexibility.

Table 5. Platform and Setup Key Specifications

Parameter	Specification	Impact
Platform Dimension	500 mm x 350 mm (LxW)	Compact size fits well within 1 m walkway,
Platform	Approx. 80 kg	Easily maneuverable
Repositioning Time	< 5 minutes	Minimal downtime during moves
Setup Time	< 2 minutes	Quick task setup and changeover

The dimensions allow safe movement in narrow aisles. Repositioning takes under five minutes, with preprogrammed routines enabling quick reinitialization for flexible deployment.

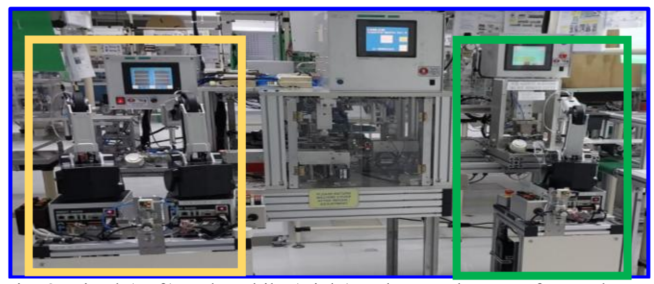


Fig. 8. Fixed (Left) and Mobile (Right) Cobot Deployment for Product B Assembly Line

Fig. 8 illustrates the dual deployment of cobots in the Product B assembly line. The yellow box on the left highlights a fixed cobot, integrated at a dedicated workstation for continuous operation. The green box on the right indicates a mobile cobot, mounted on a wheeled platform for flexible deployment across different production zones.

3.4.4 Mapping COBOT Utilization in the Production Workflow

This section identifies the integration point of the cobot within the process, which was determined based on internal analysis and computation. The shaded yellow areas indicate the locations where Cobots have been placed.

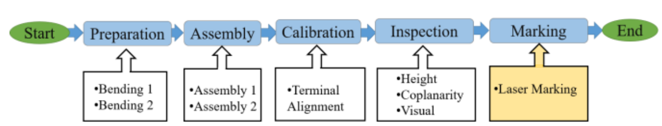


Fig. 9. Product A Process Flow

Fig. 9 shows that in the product A, a mobile cobot is placed in marking stage of the process. This leads to a reduction of 1 operator, a line balance of 87.58%.

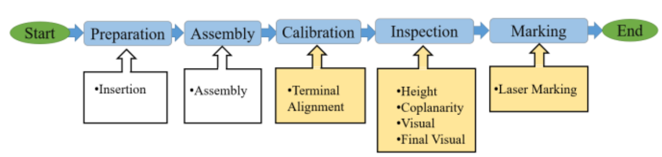


Fig. 10. Product B Process Flow

Fig. 10 shows that for Product B, a mobile cobot was integrated between the calibration and inspection stages, while three fixed cobots were deployed between height inspection, coplanarity, visual, and laser marking stages. This setup reduced operator count by two, achieved a line balance of 97.04%.

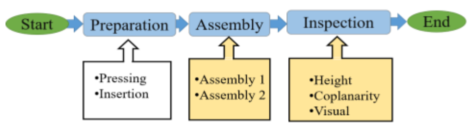


Fig. 11. Product C Process Flow

Fig. 11 shows that in Product C, 2 cobots with 1 mobile unit and 1 fixed unit were placed in between Assembly 2 to Height Inspection and Height Inspection to Coplanarity Inspection. This integration leads to a reduction of 2 operators, a line balance of 92.07%.

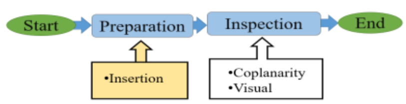


Fig. 12. Product D

Fig. 12 shows that in Product D, A mobile cobot is placed in between insertion stage to coplanarity inspection. This results in a reduction of 2 operators, a line balance of 100%.

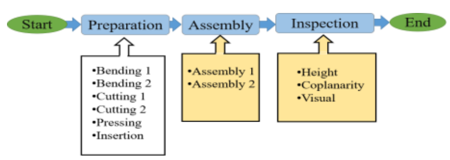


Fig. 13. Product E Process Flow

In Product E, as shown in Fig. 13, fixed cobot were placed in the Assembly and Inspection stages. This results in a reduction of 1 operator, a line balance of 97.5%.

Table 6. Cobot Integration Results

Process Line	Line Balance with Cobots	No. of Reduce Manpower	Deployed Date
Product A	87.58%	1	August 5, 2024
Product B	97.04%	2	Octobter 30, 2024
Product C	92.07%	4	June 30,2024
Product D	100%	2	December 17, 2024
Product E	97.50%	1	February 20, 2025

Table 6 provides a summary of the improvements applied to each product line, consolidating the process modifications and their respective outcomes.

3.5 Control Phase

To sustain the improvements achieved through the integration of collaborative robots into the production lines, key control actions were implemented. First, a 4M Change Record was generated to formally document changes in Man, Machine, Method, and Material. Second, Failure Mode and Effects Analysis (FMEA) was developed to identify and mitigate potential risks in the new process. Third, Work Instructions (WIs) were revised to reflect updated procedures for cobot operation. Finally, Production and Maintenance Check Sheets were updated to include new inspection points, ensuring consistent monitoring and preventive maintenance.

4.0 RESULTS AND DISCUSSION

The deployment of modular cobots in five different machines has significantly elevate overall production efficiency, with measurable improvement in line balancing and operational cost saving.

Process efficiency gains align with previous study showing balance efficiency from 40.33 % to 85.12% after automation [1]. Similarly, the 12.19 percent average increase across five products confirms cobot effectiveness in improving task distribution and supporting flexible manufacturing.

4.1 Line Balance Improvement

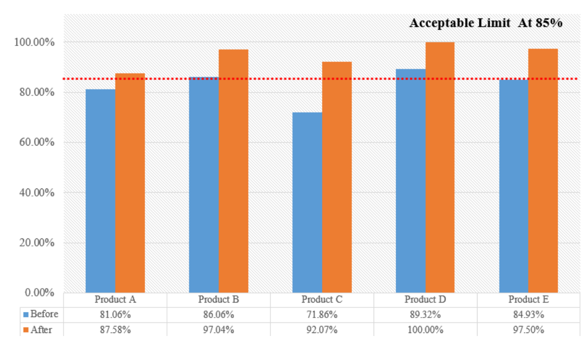


Fig. 14. Comparison of line balance performance after implementation of Modular Cobot

As shown in Fig.14, the implementation of cobot in five product line resulted an average increase of 12.19% surpassing the 85%-line balance threshold. Notably, Product C has the lowest performance of 71.86% but has the largest improvement of +20.21%. The 100% result of Product D indicates that this project was proven effective in line optimization.

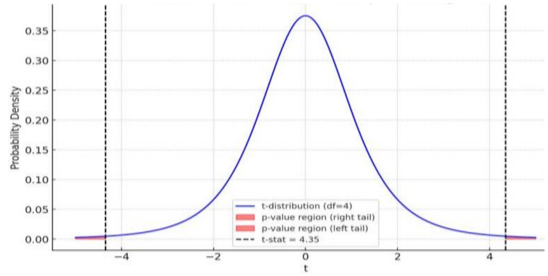


Fig. 15. T-Distribution with p-value region curve for line Balance Improvement

Fig. 15 presents the result of t-statistic: 4.35 and a P Value of 0.0204 indicating a statistically significant result at 5% level, providing strong evidence to reject the null hypothesis

4.2 Manpower Cost Saving

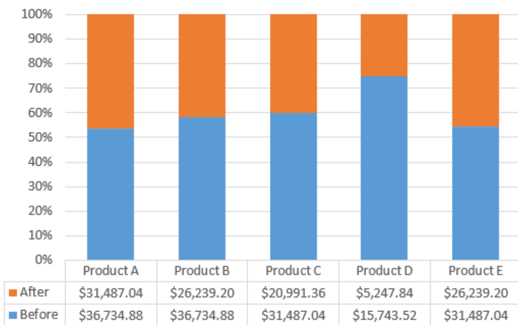


Fig. 16. Manpower cost before and after cobot deployment

Fig. 16 shows that all five product lines reduced manpower costs after implementing cobots, with total annual savings of $41,982 Products B, C, and D each saved $10,495.68, while Products A and E saved $5,247.84 each. Product D achieved the largest reduction at 66.67 percent, lowering costs from $15,743.52 to $5,247.84, indicating a significant improvement in efficiency. In comparison, Products A and E had smaller reductions of 14.28 percent and 16.67 percent, respectively, suggesting further efficiency improvements are possible.

5.0 CONCLUSION

The implementation resulted in process efficiency improvements ranging from 87.58% to 100%, alongside a reduction in manpower costs from an initial range of $36,735 to $31,487 down to a narrower range of $31,487 to $5,247, yielding an annual savings of $41,983. The integration of cobots proved to be effective within existing workflows, contributing to significant enhancements in line balance and overall process efficiency.

6.0 RECOMMENDATIONS

The integration of a low-cost modular pick-and-place robot resulted in improved overall process performance. Standardizing robot-assisted workflows can help maintain consistent performance across the production line. Continuous investigation of line efficiency is essential to identify further improvement opportunities and guide future enhancements. Future deployments should also consider ergonomics and operator interaction, with ongoing KPI monitoring to support continuous optimization.

7.0 ACKNOWLEDGMENT

The team extends appreciation to the Kaizen Office for their guidance and support, and to Top Management for their encouragement. Special thanks to the Connectors Department for providing necessary resources, and to the Factory Automation Section for their valuable contributions.

8.0 REFERENCES

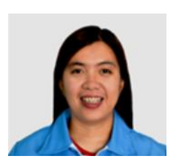
1. W. Ngamkala and S. Prombanpong, "A Productivity Improvement of an Assembly Line through Line Balancing and Automated Work-Part Feeder," *Applied Mechanics and Materials*, vol. 865, pp. 88–93, Jun. 2017, doi: 10.4028/www.scientific.net/AMM.865.88.

2. E. K. Zavadskas, Z. Turskis, and J. Tamosaitiene, "Multi-criteria decision-making methods for construction management," *Technol. Econ. Dev. Econ.*, vol. 26, no. 2, pp. 406–429, 2020, doi: 10.3846/tede.2020.12211.

9.0 ABOUT THE AUTHORS

This section describes the author's educational background and employment history.

Allison R. Altea, a Jr. Automation Specialist at PMI. His expertise in multiple programming languages contributes to the automation project by developing software systems and robot systems.



Precious A. Mantala, a Jr. Automation Specialist at PMI. With strong expertise in PLC and robot programming she contributes to automation projects by developing software systems and robotic systems.

Aldous A. Tamolang, a Sr. Automation Specialist at PMI. An expert in automation, he specializes in PLC programming and vision system integration. He played a key role in developing automation at PMI.