Proceedings of the 2nd World Congress on Industrial Engineering and Operations Management
Windsor, Canada, October 14-16, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/WC02.20250190
Published: October 14, 2025

Micro-Motion Lean using MODAPTS: Enhancing Productivity in a Tier-1 Automotive Seatbelt Assembly Plant

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Abstract

This paper presents a focused lean improvement case on a two-operator seatbelt sub-assembly cell at a North American Tier-1 automotive supplier, producing above its designed combined cycle time (actual ~32.2 sec vs. designed 30.3 sec). Hidden losses were identified in motion, layout, and sequencing rather than machine performance. A structured improvement approach combined Value Stream Mapping (VSM), Modular Arrangement of Predetermined Time Standards (MODAPTS) motion coding, Yamazumi load analysis, and low-cost physical rearrangement. Baseline MODAPTS breakdown revealed avoidable walking, redundant reaches, one-handed idle, and a micro-wait at a shared press between the two workstations representing on average 3-6 theoretical seconds of recoverable time per cycle. Targeted countermeasures such as point-of-use material repositioning, two-hand synchronous picking, workload balancing, press control relocation and standardized micro-sequence delivered a 13.2% cycle time reduction, lifted balance efficiency to 99.6%, and reduced lead time by over 21.9%, all without capital automation. A disciplined combination of micro-motion analysis and lean flow tools is shown to significantly enhance manual assembly performance. This case demonstrates that targeted method and layout refinements are sufficient to unlock latent capacity, enabling the system to exceed its initial design specifications.

Keywords
Lean manufacturing; MODAPTS; Line balancing; Layout optimization; Assembly efficiency

1. Introduction
Manual seatbelt buckle sub-assembly requires strict adherence to takt time, as even small deviations can increase overtime, strain schedules, and heighten operator workload. In the studied two-operator assembly cell, a consistent gap existed between the designed combined cycle time of 30.3 seconds and the observed ~32.2 seconds, despite stable equipment uptime.

Prior research highlights that hidden capacity losses in established automotive assembly lines are often caused by motion inefficiencies, sub-optimal micro-layouts, and uneven task allocation rather than equipment constraints (Khairai and Khalil 2024; Badhotiya et al. 2024; Hines and Rich 1997). Traditional lean observation tools can flag broad inefficiencies, but deeper recovery requires systematic work measurement. Predetermined motion time systems such as MODAPTS provide a structured way to code and quantify micro-motions, helping prioritize low-cost adjustments before pursuing automation (Wu et al. 2016).

This study documents an improvement effort in a Tier-1 supplier's buckle sub-assembly process, where MODAPTS was combined with Yamazumi balancing, Value Stream Mapping (VSM), and ergonomic micro-layout redesign. The work quantifies value-added (VA), necessary non-value-added (NNVA), and non-value-added (NVA) elements; identifies root causes such as operator rotation effects, walking paths, and shared-station overlap; and proposes a future state that reduces cycle time without compromising quality. By focusing on walking, redundant reach, one-hand idle segments, and minor inter-operator waits, the project achieved performance gains beyond the original design target without capital expenditure. The approach is structured to create a replicable framework adaptable to similar small-footprint manual assembly lines.

1.1 Objectives

The cell under study showed a persistent gap between its designed and actual combined manual cycle, with indications that latent waste resided in micro-motions and spatial arrangement rather than equipment capability. To move beyond a generic lean adjustment and to document replicable, low-cost capacity release, the project was structured around the following five focused objectives. (i) Map the current process and classify activities into VA, NNVA, and NVA using VSM and MODAPTS. (ii) Determine workload imbalance with Yamazumi charts and identify opportunities for rebalancing. (iii) Design and trial low-cost layout changes and micro-method improvements to eliminate excess walking, reach, and idle time. (iv) Reduce combined cycle time to 30.0 seconds or below, thereby surpassing the original design specification. (v) Establish a practical sustaining plan through measurement validation, statistical monitoring, and ergonomic assessment.

2. Literature Review

Lean manufacturing emphasizes steady flow by eliminating waste such as motion, waiting, and uneven workload. Liker (2021) stresses that reliable performance comes from standard work and workplace organization, while Rother and Shook (2003) show how VSM reveals gaps between material and information flow. Even mature automotive plants continue to face hidden motion and layout waste, which reduce capacity and add ergonomic strain (Badhotiya et al., 2024; Khairai and Khalil, 2024). Stopwatch studies become inconsistent when cycles involve many micro-motions. MODAPTS offers a library of predetermined motion times, providing faster and more repeatable measurement (Barnes, 1980; Wu et al. 2016). Studies show that combining MODAPTS with video review identifies redundant or one-handed motions before workplace redesign, while its repeatability supports low-cost justification of method changes (Eisbrenner Productivity Group, 2019).

Workload imbalance also drives inefficiency. Yamazumi charts are widely used to visualize operator loads, making bottlenecks and non-value-added clusters visible (Chan et al., 2023). Integrating Yamazumi with lean observation can reduce cycle time without automation (Hillali et al., 2024; Khairai and Khalil, 2024). Researchers agree that human work should be leveled before adding robotics (Sordan et al., 2022).

Layout design strongly affects motion efficiency. Compact cells and point-of-use placement reduce walking and variation (Badhotiya et al., 2024). Small ergonomic changes, such as repositioning bins or controls, often yield more benefit than early capital investment (Hillali et al., 2024; Mortada and Soulhi, 2023). Sustaining these gains requires leader standard work and simple visuals, which provide a foundation for later digital or advanced tools (Belghiti et al., 2025). While MODAPTS, Yamazumi, and low-cost cell adjustments are well-documented, few studies combine all three in small, two-operator automotive safety cells. Evidence of surpassing original design cycles through method and layout optimization alone remains limited (Badhotiya et al., 2024; Sordan et al., 2022). This study addresses that gap.

3. Methods

This study adopted a structured lean problem-solving approach to improve two linked operations, referred to as Process 1 and Process 2. Emphasis was placed on MODAPTS as the main tool for identifying improvement opportunities. Instead of a separate scoring matrix, changes were prioritized by three practical factors: (i) total recoverable NNVA and NVA seconds per cycle from the MODAPTS breakdown, (ii) ease of implementation through simple layout or method adjustments, and (iii) expected impact on workload balance.

To analyze the processes, a combination of lean and industrial engineering tools was applied. VSM was used to map the process flow and separate VA, necessary but NNVA, and NVA activities (Ohno 1988; Rother and Shook 1999). Stopwatch study provided baseline cycle times, while MODAPTS enabled detailed motion analysis by breaking tasks into elemental actions such as reach, grasp, move, and position (Barnes 1980; Wu et al. 2016). Yamazumi charts were constructed to visualize workload balance between operators (Chan et al. 2023), and 5W1H with cause-and-effect analysis was applied to identify root causes of inefficiencies (Hines and Rich 1997). The integrated use of VSM, MODAPTS, time study, Yamazumi charts, and structured root cause analysis ensured both macro-level and microlevel insights. This approach enabled systematic identification of waste which was catered through low-cost improvements without the need for major equipment changes.

4. Data Collection

Data was collected through continuous observation of the two linked operations, referred as Process 1 and Process 2, on the seatbelt sub-assembly line of a Tier-1 automotive supplier. The observation period spanned 6-8 hours of production under normal operating conditions. Two complementary techniques were applied: direct stopwatch timing and video recording. Stopwatch study provided baseline task durations, while video review enabled frame-by-frame verification to reduce observer bias and ensure consistency (Barnes, 1980; Wu et al. 2016). A total of 24 cycles per process were recorded, giving a sufficient sample size for later statistical analysis.

Operator performance was evaluated under both internal and external rotation scenarios to reflect real shop-floor practices. Initially, Operator A, worked on Process 1 while Operator B, worked on Process 2. After 30 minutes, an internal rotation was performed, with Operator B, moving to Process 1 and Operator A, to Process 2. Subsequently, an external rotation introduced two additional operators (C and D), who replaced the original pair. This sequence allowed the dataset to capture natural variability across operators as well as workload shifts due to rotation. The collected cycle-time data was structured and analyzed using a combination of lean and industrial engineering tools. Operator rotation intervals were standardized (30 minutes for internal swap, 60 minutes for external replacement) to minimize the influence of fatigue, individual speed, or learning effects.

5. Results and Discussion

5.1 Numerical Results

Operator Averages and Rotations:

Cycle time data were collected across two workstations using 24 values per process, each operated by three different individuals. In Process 1, the cycle times recorded were 15.72s (Operator a), 16.39s (Operator b), and 17.70s (Operator c), resulting in an overall average of 16.60 ± 0.89s. Although all operators performed slightly longer than the designed cycle time of 15.70 s, the variation between them remained modest. For Process 2, the observed cycle times were 15.71s (Operator b), 14.90s (Operator a), and 16.49s (Operator d), with a calculated average of 15.70 ± 0.71s. The design target here was 14.60s, suggesting that the actual performance exceeded the target but again showed only minor fluctuations across operators. Together, the combined actual cycle time shown in Figure 1 sums to approximately 32.30s, compared to the designed combined cycle of 30.30s. The observed deviations from design were under ±1s per process, highlight a consistent performance as opposed to wide variability among operators.

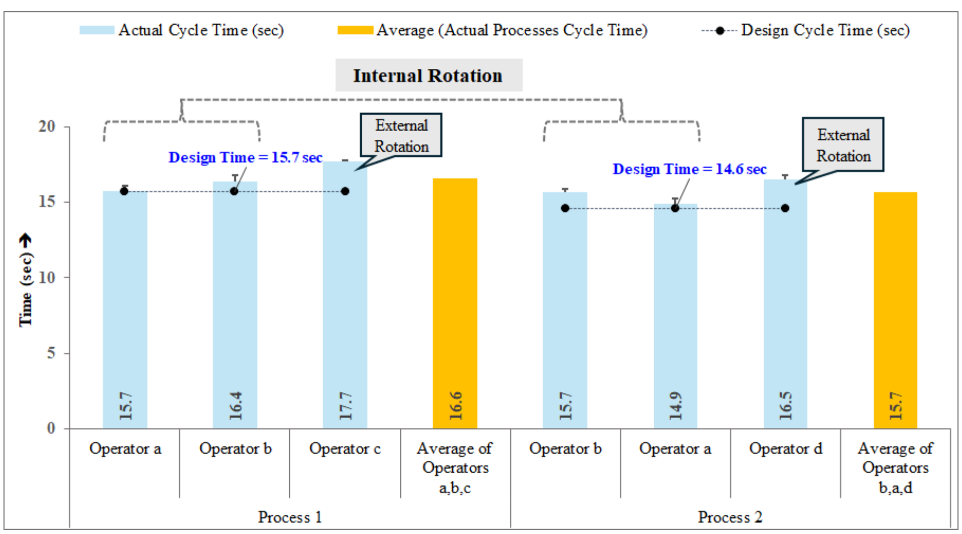

Figure 1. Operator-wise actual cycle times comparison with design cycle times graph

These results indicate that while operator performance is quite stable, both Process 1 and Process 2 are lagging behind the designed targets primarily from systematic inefficiencies. This reinforces the focus on redundant motions, layout constraints, or workload imbalance rather than individual operator performance.

MODAPTS Analysis:
The MODAPTS coding according to process breakdown and calculations are summarized in Table 1 and Table 2. This analysis revealed avoidable walking, redundant reaches, and one-handed idle periods at the CVR press. The total motion codes equaled 130+120.5 = 250.5 MODs, which translates to 32.4 seconds when multiplied by the standard conversion factor (0.129s/MOD). This value is almost identical to the stopwatch/video study result of 32.3 seconds, with a deviation of only 0.34%, well within the accepted ±3% range. This strong agreement confirms the reliability of the MODAPTS analysis and validates its use for identifying 2–6 seconds of recoverable time per cycle through systematic motion redesign and workload balancing, without requiring capital automation.

Table 1. MODAPTS coding based on motion for seatbelt sub-assembly at process 1

Sr#	Work element description	MODAPTS Code	MODs	Classification
1	Pickup wire harness	M3G3 M3P0	9	NNVA
2	Move 1 pace	W5	5	NVA
3	Pickup boot and place in jig	M5G1 M4P2	12	VA
4	Press foot pedal for the machine	F3	3	NNVA
5	Route the wire though the boot	E2M2P2	6	VA
6	Pickup LWR cover load to machine and clip wire harness (Allowance 1 sec)	M4G1 M4P2, M2G1 M2P5 10	31	VA
7	Unload piece	M2G3	5	NNVA
8	Move 1 pace	W5	5	NVA
9	Pickup buckle assembly	M4G1	5	NNVA
10	Assemble parts	M2P2	4	VA
11	Move 2 paces	W5	10	NVA
12	Plug the wire connector and load assembly on CVR Press (both hands)	E2M3P5 M5P2	17	VA
13	Press start button of CVR Press machine	M5G0 M1P2	8	NNVA
14	Walk back	W5	10	NVA
Total			**130**	

Table 2. MODAPTS coding based on motion for seatbelt sub-assembly at process 2

Sr#	Work element description	MODAPTS Code	MODs	Classification
1	Remove connector and pickup UPR CVR to load in machine	M4G3 M2P0, M4G1	14	NNVA
2	Remove finished part from nest and place UPR CVR in machine	M4G1 M4P5	14	VA
3	Move 1 pace	W5	5	NVA
4	Hang the piece on tape fixture and grab tape piece, wrap wire webbing (2 turns)	M3P2, M4G1 M4P2, 2M1P0	19	VA
5	Pull/slide the boot to cover the sub-assembly	M2G1 M2P0	5	VA
6	Remove the piece and fix onto the hook of pull machine, pull to confirm fitment	M2G3, J2, M3P2 X4	16	VA
7	Grab clip, insert it into the piece	M3G1, E2M2P5	13	VA
8	Place the assy. into clip press for clip fitment, then unload the part assy.	M3P2 M2G1	8	VA
9	Move 1 pace	W5	5	NVA

10	Twist the plastic clip on wire before placing it on tray before forwarding it	M2G3, U0.5, M4P2	11.5	NNVA
11	Walk back	W5	10	NVA
Total			**120.5**	

5.2 Graphical Results

Value Stream Mapping (VSM):

The stopwatch dataset was translated into a current state VSM to capture the end-to-end material and information flow, and to separate VA, NNVA, and NVA activities (Rother and Shook, 2003). The VSM is presented in Figure 2 to visualize the material and information flow in the two-operator seatbelt sub-assembly cell.

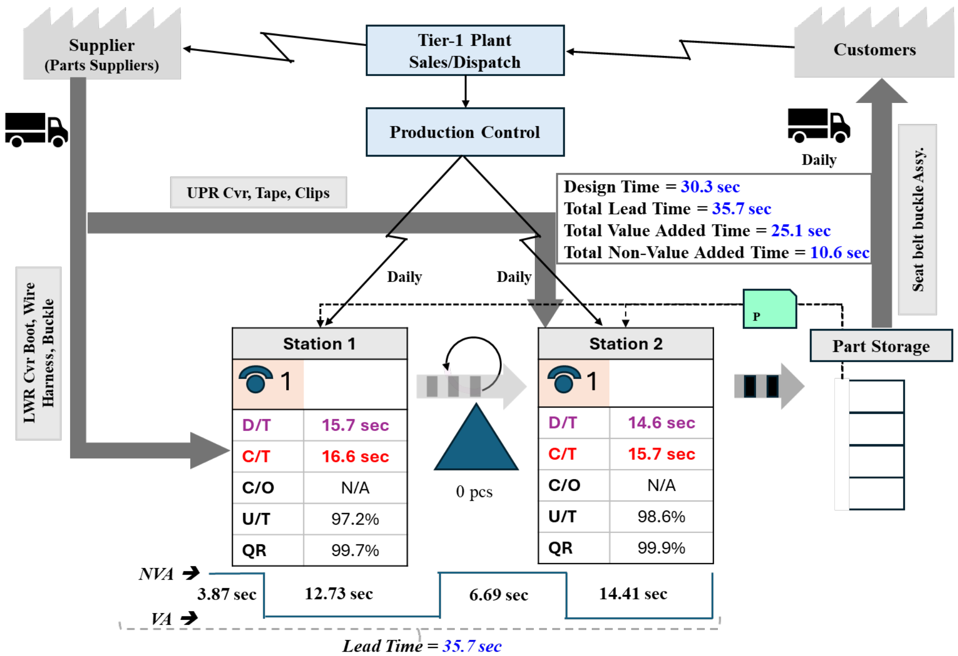

Figure 2. Current-state Value Stream Map showing excess motion and lead time, with unstable push/pull flow between stations due to the operation time of cover press machine

It shows that while the designed combined cycle time was 30.3s, the actual measured time reached 32.3s, producing a lead time of 35.7s. The VSM further identified that only 25.1s of the total was VA, while 10.6s was NVA. As shown in Figure 2, system suffered due to excess operator motion. The overlapping CVR press created an unstable push/pull flow, resulting in push conditions (and occasional pull) due to operator's speed mismatch. Buffer was unavailable due to single piece flow operation, which further reinforces the need for workload balancing and layout optimization.

Yamazumi Chart Analysis:

To further assess workload distribution, the operator-level results from Table 1 (Process 1 MODAPTS breakdown) and Table 2 (Process 2 MODAPTS breakdown) were consolidated into a Yamazumi chart which stacks work elements. The results in Figure 3 confirmed that Process 1 averaged 16.6s against its design of 15.7s, while Process 2 averaged 15.7s against its design of 14.6s. This imbalance raised the combined cycle time to 32.3s compared to the designed 30.3s, confirming that Process 1 consistently acted as the bottleneck. MODAPTS results further indicated that non-value-added elements such as redundant reaches, idle time at the shared CVR press, and non-standard sequences contributed 2–6 seconds of recoverable time per cycle.

A closer review of the task breakdown identified several underlying causes of imbalance. First, operator-related variation was observed, as differences in working speed and the occasional use of non-standard assembly sequences created inconsistency between rotations which was not significant as mentioned earlier. Second, shared machine overlaps at the CVR press forced one operator to wait while the other completed the cycle, since no buffer existed between stations. Third, ergonomic and material placement issues contributed to excess reaching and repositioning, particularly where bins and components were not arranged within natural reach zones. Fourth, method and sequence gaps were evident, as the lack of standardized micro-operation sequences allowed redundant and one-handed motions to persist. Finally, layout design factors such as workstation spacing and suboptimal press control positioning further contributed to unbalanced workloads and increased non-value-added activity.

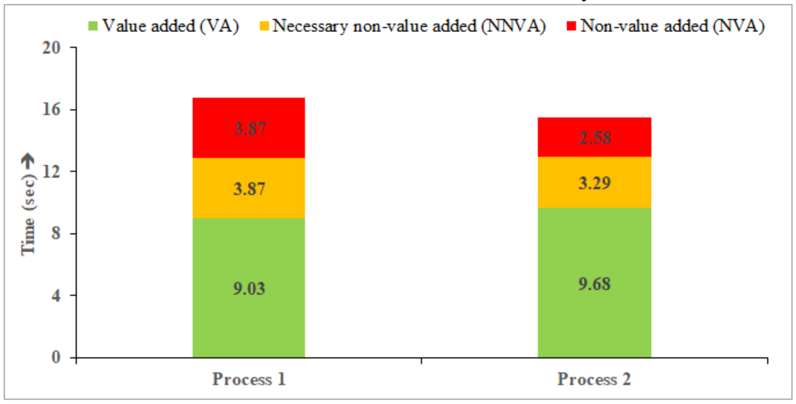

Figure 3. Yamazumi chart of Processes 1 and 2 highlighting imbalances, with Process 1 as the consistent bottleneck

These causes generated the observed motion waste, idle waiting, and over-cycle times. They provide the direct basis for the proposed improvements, which focus on workload rebalancing, ergonomic layout changes, and standardization of operator methods.

5.3 Proposed Improvements

The current layout forces operators to take unnecessary walking steps and reach across bins, which contributes to NVA motion. As shown in Figure 4 and Figure 5 the proposed redesign contracts the workstation footprint and repositions bins and controls at point-of-use. Quantitatively, the layout revision through minor improvements will reduce the cumulative work cell width from 108 inches to 75 inches, saving 33 inches of operator walking per cycle. This equates to approximately two steps saved per operator (2W5 = 10 MODs each). For two operators, this reduction equals 20 MODs, corresponding to 2.58 seconds per cycle when converted using the MODAPTS constant (0.129 sec/MOD).

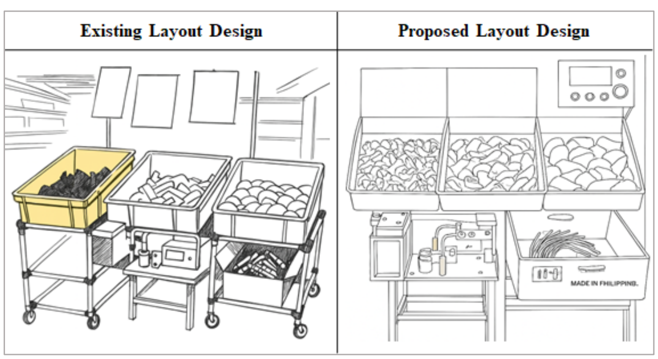

Figure 4. Process 1 workstation layout: existing vs. proposed

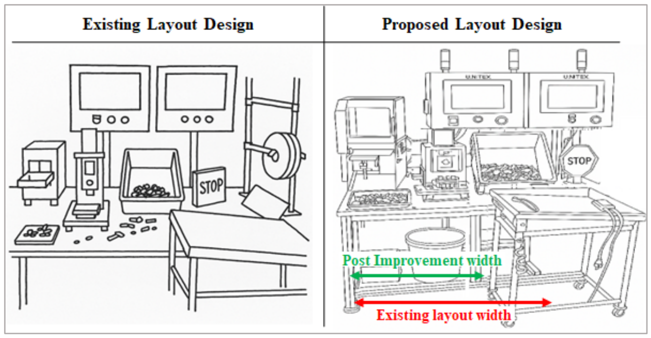

Figure 5. Process 2 workstation layout: existing vs. proposed

In addition to layout changes, the assembly sequence will be further refined using MODAPTS motion coding and several improvements will be made. Firstly, parallel execution of left- and right-hand motions at the CVR press will replace sequential one-hand operations, thereby eliminating idle time. Secondly, repetitive pick-and-place motions, such as the pickup of the wire harness and upper cover, will be combined into a single step. Third, NNVA activities will be reordered so that they align more closely with VA steps, creating a smoother flow. Finally, redundant NVA elements, including repeated single-hand placements and excess walking, will be eliminated to reduce fragmentation.

With these refinements, the total workload will reduce from 250.5 MODs (≈32.3 sec) to approximately 206 MODs (≈27.9 sec) despite adding 5% allowances. This represents an expected saving of 4.5 seconds per part, beyond the 2.6 seconds already achievable through layout revision. The revised Yamazumi chart in Figure 6 for Process 1 and Process 2 showing workload distribution before and after proposed improvements. This further illustrates the improved workload distribution of activities and balance efficiency after applying these methods and layout changes.

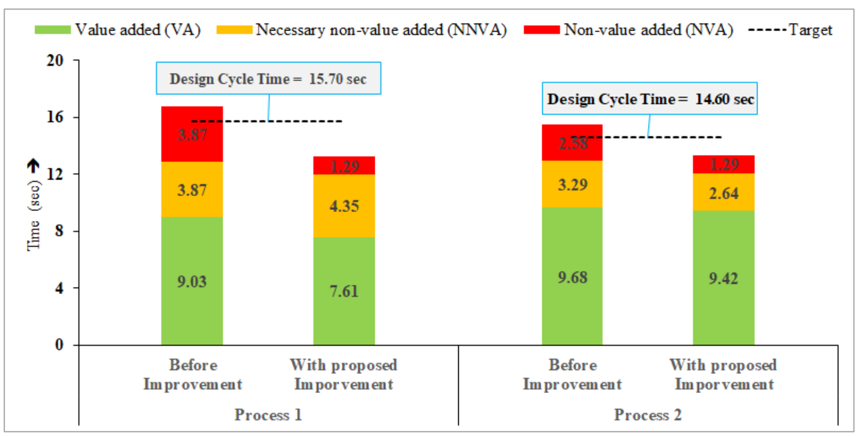

Figure 6. Revised Yamazumi chart after proposed layout and MODAPTS refinements

Together, layout optimization and MODAPTS-based sequence redesign will deliver an improved line balance efficiency from 93.5% to 99.6%, VA time by 3.7%, reduction in combined cycle time by 13.6% with total projected saving of 4.5 sec/cycle, surpassing the original design target of 30.3 seconds without requiring capital automation.

5.4 Validation

To ensure that the projected improvements translate into sustainable performance, the revised cycle time of 13.35 sec will be validated through pilot implementation and statistical monitoring. Validation will not only confirm the accuracy of the MODAPTS-based projections but also demonstrate their practicality under real production conditions. Ergonomic impacts, and rotation practices will be considered to ensure that the improvements are robust and repeatable. The expected benefits are summarized in Table 3, which consolidates the projected cycle-time reduction, capacity gains, and financial impact. The combined effect of layout optimization and MODAPTS-based method redesign will yield an additional +1,057 parts/day at the target volume of 1600 units.

Table 3. Validation of proposed improvements with future estimates

Scenario	Total cycle Time (sec)	Extra Parts/Day	Est. Benefit ($/day)*	Remarks
Baseline (Actual/Observed)	32.3	–	–	Current performance
Design Time (Target)	30.3	–	–	Original line target
After Layout Optimization	~29.7	+620	$12,400	Walking & motion waste reduced
After MODAPTS Refinement	~28.6	+437	$8,740	Parallel & sequence optimization
Combined Improvements	~28.8	+1,057	$21,140	Total benefits: layout + MODAPTS

** Based on estimated profit contribution of $20 per part.*

Future validation will include hypothesis testing of cycle time distributions to statistically verify the significance of reductions, ergonomic assessments to confirm reduced operator burden, and Return of Investment (ROI) tracking to ensure that payback is achieved within the early weeks of implementation.

6. Conclusion

The findings demonstrate that even in mature automotive lines, untapped capacity often resides in micro-motions, workstation layout, and operator balance rather than in machinery or automation. By applying MODAPTS alongside lean flow tools, this study established a structured approach for identifying and quantifying such hidden wastes. Unlike conventional stopwatch studies, the motion-coded framework ensures repeatability, reduces subjectivity, and provides a stronger basis for justifying changes to management. A notable contribution of this work is showing that significant gains an expected 4.4 seconds per cycle reduction, with balance efficiency approaching 99.6% from 93.5%, can be realized with minimal capital outlay (<$1,200) for operators training, parts bins, and layout improvements. Beyond throughput, the proposed improvements enhance ergonomics by shortening walking paths and reducing one-handed idle, thereby supporting operator well-being and long-term sustainability of the process.

For practitioners, this case highlights a low-cost pathway to productivity improvement without reliance on automation. For researchers, it offers a replicable methodology that integrates MODAPTS, Yamazumi, and VSM into a practical improvement cycle. Future pilot trials will validate the framework under production conditions and extend its applicability to other small-footprint manual assembly cells in the automotive sector and beyond.

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Biographies

Usama Tariq recently completed a Master of Engineering in Mechanical Engineering (Automotive) at the University of Windsor, Canada. He has nearly five years of industry experience at Hyundai Pakistan, where he progressed from Trainee Engineer to Assistant Manager, leading roles in supplier management, production support, process optimization, and quality systems. His expertise spans lean manufacturing, supplier development, ISO 9001 compliance, and continuous improvement, with practical experience in part maturation, audits, process optimization, and motion/time studies. He has worked across a wide range of automotive commodities including electronics, plastics, sheet metal, interiors, seating, and energy systems. A certified Six Sigma Green Belt, he is an active member of the Ontario Society of Professional Engineers (OSPE) and the Pakistan Engineering Council (PEC). His research interests include lean optimization, MODAPTS-based motion analysis, and productivity improvement in automotive assembly systems.

Samuel Adu is pursuing a Master of Engineering in Mechanical Engineering (Automotive) at the University of Windsor, Canada. He holds more than two decades of professional experience in the automotive sector in Ghana, where he worked extensively on powertrains, chassis, suspension, HVAC systems, and hybrid battery technologies. His background includes advanced diagnostics using OEM software, apprenticeship training, and process improvement initiatives. He also holds a Lean Six Sigma Green Belt certification. His current research interests focus on sensors and controls for hybrid and electric vehicles, and the application of lean tools such as MODAPTS to enhance efficiency in manual assembly systems.

Dr. Sardar Asif Ayyub Khan holds a Ph.D. in Manufacturing Systems Engineering, an MBA, an M.S. in Manufacturing Engineering, B.S. in Electrical Engineering, and is an active member of IEOM, INFORMS, SME, and IEEE. He is a recognized leader in lean manufacturing, continuous improvement, and operational excellence with more than 30 years of combined industry and academic experience. He currently serves as Continuous Improvement Lead at Stellantis Parts and Services Supply Chain North America and as an Adjunct Professor in the Faculty of Engineering at the University of Windsor. At Stellantis, he has led major process transformations and delivered sustained performance improvements across supply chain operations. In academia, he mentors graduate engineering students, linking industrial practices with classroom learning.