

Assessment Level 7

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Abstract

This report presents a comprehensive simulation-driven optimization of Alpha Precision Components' (APC) 3-machine CNC piston machining cell using Visual Components software, systematically addressing the baseline inefficiencies inherent in the previous robotic work cell design. The initial linear-curved layout, featuring three dedicated Fanuc M-10iA/8L robots for machine tending (R1 for the Haas ST-30 lathe, R2 for the VF-1 VMC, and R3 for the UMC-500 5-axis mill), conveyors (IC, TC1, TC2, and OC), and a manual inspection station, produced a disappointing 143 parts per 8-hour shift at 200 s interarrival variability. This underperformance was primarily hampered by unbalanced robot utilization, excessive queue build-up at TC2, prolonged operator motion waste between OC and inspection, and suboptimal floorspace use in the curved configuration, risks that threatened contract delivery, quality, and scalability.

Strategic application of lean manufacturing principles, including cellular one-piece flow, takt time-driven line balancing, and JIT buffer reduction, resulted in a redesigned compact linear cell layout with only two robots. R1 now handles both lathe and VF-1 tending, while R2 focuses on the 5-axis bottleneck, shortening conveyor paths and repositioning inspection for minimal walking. This transformation enhanced throughput by 44% to 206 parts per shift (25.75 parts/hour), decreased average cycle time by 12.5% (200 s to 175 s), reduced max TC2, and boosted operator value-adding. VC visualization and comparative metrics corroborated these advantages, with trade-offs such as capital savings from fewer robots and improved ergonomics favouring net benefits under ISO 10218-2/BS EN safety standards and HSE guidelines.

A critical literature synthesis encompassing Flexible Manufacturing Systems (FMS), lean robotics, VC simulation capabilities, and safety trends supports the findings, demonstrating how SMEs like APC can achieve substantial productivity gains (20–50% per case) via accessible digital tools without major capital expenditure. Implications include de-risked commissioning, enhanced competitiveness for APC, and scalable Industry 5.0 models for precision engineering. Limitations suggest future extensions like AI path optimization, co-bot integration (ISO/TS 15066), and real-time digital twins for live operations.

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Abbreviation

APC = Alpha Precision Components

R = Robot

IC = Inlet Conveyor

TC = Transitional Conveyors

OC = Outlet Conveyor

FMS = Flexible Manufacturing system

SMEs = Small and Medium-sized Enterprises

KPI = Key Performance Indicator

VSM = Value Stream Mapping

VC = Visual Components

WIP = Work in progress

1. Introduction

1.1 Background to APC Piston Machining Cell

Alpha Precision Components (APC) is a Tier-1 supplier specializing in high-performance pistons for automotive and motorsport engines. recently secured a contract for a turbocharged 4-cylinder engine platform requiring rapid production ramp-up at low unit cost and high quality. To meet this demand, APC's engineering team designed a dedicated 3-machine CNC work cell incorporating a Haas ST-30 lathe for turning blank pistons, a Haas VF-1 vertical machining centre for milling slots, pin bores, and oil galleries, and a Haas UMC-500 5-axis mill for crown and skirt finishing. Machine tending is handled by three Fanuc M-10iA/8L robots (R1 for lathe, R2 for VMC, R3 for 5-axis), supported by an inlet conveyor (IC), transitional conveyors (TC1, TC2), an outlet conveyor (OC), pallet storage, and a manual inspection station.

The process flow begins with raw parts arriving on Inlet Conveyor at variable interarrival intervals, loaded by Robot 1 into the lathe, unloaded to Transitional Conveyor 1, transferred sequentially via Robot 2 and Robot 3 to VF-1 and 5-axis mill, then to Outlet Conveyor for operator inspection and finished goods palletizing. Operating parameters include robot joint speeds at 50%, conveyor speeds at 500 mm/s, operator walking at 1200 mm/s unloaded/1000 mm/s loaded, over an 8-hour shift. This initial design, adapted from existing shop floor assets without formal optimization, aims to balance throughput with quality but reveals preliminary issues like queue build-up and resource imbalance, prompting simulation-driven redesign.

1.2 Problem Statement and Objectives

The initial APC cell design exhibits critical inefficiencies, including insufficient throughput to match contract demands, excessive queue accumulation on transitional conveyors, a low operator value-adding ratio during inspection, and unbalanced resource utilization. These result from suboptimal layout causing motion waste, blocking or starvation between operations, and poor floorspace use limiting scalability—risking missed deliveries, overtime costs, quality risks from rushed inspection, and constrained expansion.

This report addresses these via Visual Components simulation:

- Recreate and validate the baseline model.
- Quantify performance metrics (throughput, cycle time, WIP, utilization).
- Identify bottlenecks using lean analysis.
- Redesign layout for improved flow.
- Compare optimized results.

2. Literature Review

2.1 Robotics and Automation in Flexible Manufacturing Systems

Flexible Manufacturing Systems (FMS) integrate robotics and automation to enable rapid adaptation to varying production demands, such as APC's piston contract requiring high-volume, precision machining with minimal reconfiguration. Core to FMS are multi-axis industrial robots like the Fanuc M-10iA/8L series, optimized for machine tending in CNC cells loading-unloading lathes, VMCs, and mills with cycle times >3 min, achieving >90% spindle utilization via idle-time sequencing across 2-4 machines (FESS Group, 2026).

Recent advancements (2024-2026) emphasize AI-driven path optimization and cyber-physical systems (CPS), where IoT sensors/digital twins enable real-time monitoring of forces, wear, and vibrations, boosting productivity by 30-45% while cutting costs 25% through adaptive control (Advanced Manufacturing Development LLC, 2026). In automotive/piston-like applications, robotic cells with in-line gauging reduce scrap from 2% to 0.3% via closed-loop offsets, supporting lights-out operation (AZoRobotics, n.d.). However, critiques note challenges in legacy integrations like APCs, where unbalanced tending leads to queues, addressed via FMS central controls for interoperability. This serves as the basis for the APC baseline, highlighting the need for simulation-validated enhancements.

2.2 Lean Principles for Process Optimisation

Lean manufacturing principles, originating from Toyota Production System, eliminate waste (Muda: overproduction, waiting, transport, excess motion/inventory, defects) to maximise value flow, directly applicable to APC's unbalanced CNC cell. Key tools include takt time shown in equation 1 (Shinde, 2025),

$$\text{Takt Time} = \frac{\text{Available Time}}{\text{Customer Demand}} \quad \text{Eq 1}$$

Value Stream Mapping (VSM) visualises flow, distinguishing value-add [machining/inspection] from non-add [conveyor waits] (sansmachining, 2025), often integrated with simulation for dynamic what-ifs, reducing lead times 30-50% in CNC facilities. Line balancing reapportions tasks to <takt, while JIT minimises buffers/inventory; Kaizen drives continuous iteration. In robotic cells, lean robotics boosts spindle utilisation >85% by slashing load/unload to 6-12 s, cutting scrap 40-60% via gauging yet requires simulation to validate, as over-automation risks rigidity. Critiques highlight hybrid human-robot needs for APC-like SMEs, where lean-simulation hybrids optimise legacy systems (Winslow Automatics Inc., 2025); (Sevella, et al., 2025).

2.3 Simulation Modelling with Visual Components

Visual Components (VC) is one of the leading 3D discrete-event simulation platforms for modelling, visualizing, and optimizing manufacturing systems, featuring drag-and-drop libraries of more than 1 million CAD models (robots like Fanuc M-10iA, Haas CNCs, and conveyors) for rapid FMS prototyping. Its physics-based engine simulates kinematics, collisions, signals, and variability, enabling offline programming (OLP) and what-if analyses to predict throughput before physical build (Automation International, 2025).

VC's statistics dashboard tracks KPIs cycle times, utilizations, queues, and operator paths via properties, exporting to Excel or CSV for lean VSM, e.g., Michelin used point-cloud imports for layout optimization, cutting iterations 50% and validating ergonomics (Automation International, 2025). In CNC/robot cells, VC quantifies bottlenecks and tests re-layouts for 20-40% throughput

gains. Visual Components identifies potential issues early in the process, reducing the need for physical prototypes and ensuring a smoother start-up phase (Visual Components, 2026).

2.4 Safety, Standards, and Emerging Trends

Robotic systems must comply with high safety standards to mitigate risks like crushing, collision, or unexpected motion in human-integrated cells like APCs. Operators access OC/inspection near robots. ISO 10218-1:2025 [industrial robots] mandates inherent safe design, for example, speed & force limits, emergency stops, etc. while ISO 10218-2:2025 covers cell integration, clarifying manufacturer roles, incorporating ISO/TS 15066 co-bot safety, and adding cybersecurity/end-effector rules. UK equivalents (BS EN ISO 10218, HSE HSG43) require risk assessments (PUWER/ISO 12100), perimeter guarding (ISO 13855), and interlocks (ISO 14119).

Emerging trends include co-bots for collaborative tending, reducing APC's manual inspection risks; digital twins for virtual risk validation; and CPS/AI for predictive safety. Automotive FMS leverages these for 50% faster changeovers, but challenges persist in legacy upgrades—simulation ensures compliance pre-build. For APC, redesign must balance throughput with ISO-aligned operator paths (IML Group PLC, 2026); (Panigrahi, 2025).

3. Baseline Model Development

3.1 Model Resources and Layout Recreation

The baseline APC cell layout (Figure 1) was provided as a Visual Components template, accurately representing the initial engineering design with a Haas ST-30 lathe, a VF-1, and a UMC-500 5-axis mill in a rectangular arrangement. Resources matched specs: three Fanuc M-10iA/8L robots (R1-R3) for tending, conveyors (IC inlet, TC1/TC2, OC outlet at 500 mm/s), pallet racks, and inspection station.

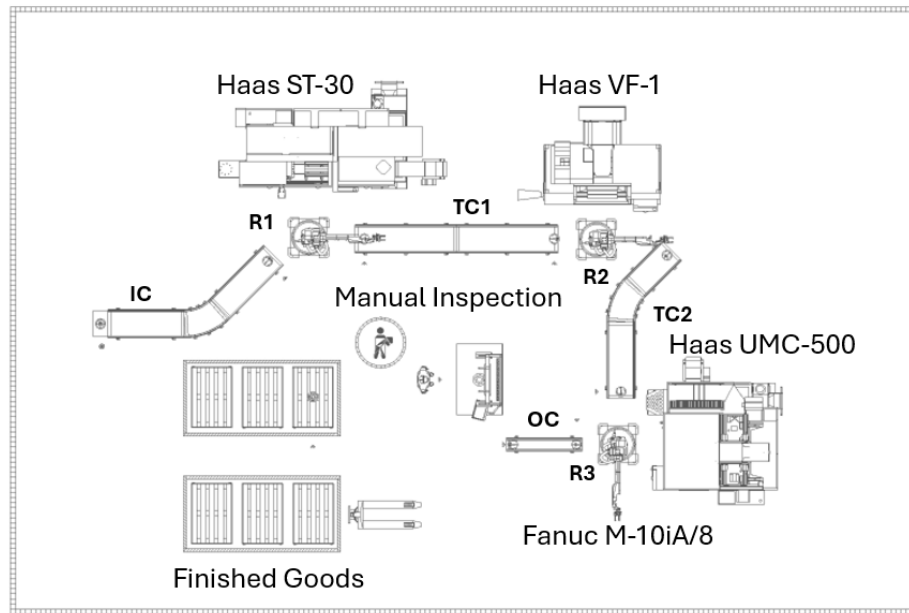


Figure 1. Given layout of the visual components.

3.2 Process Logic and Control Requirements

The Process tab in Visual Components was utilised to implement the process flow for the provided APC engineering template, sequencing operations from feeder through to palletising. Figure 2 illustrates the full flow: raw parts from feeder to inlet conveyor, R1 loads Haas ST-30 lathe, unloads to TC1; R2 transfers to VF-1, unloads to TC2; R3 to UMC-500 5-axis, unloads to OC; operator inspects before finished pallet

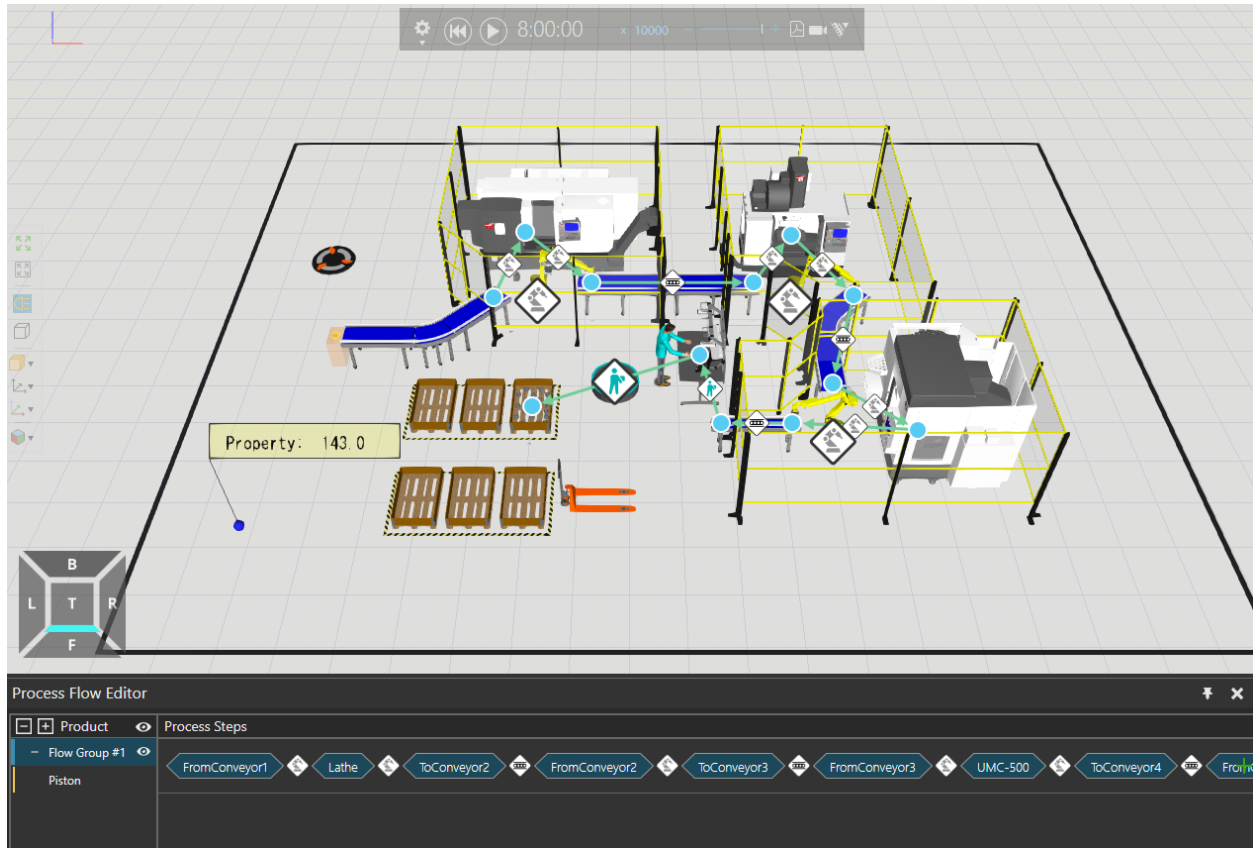


Figure 2. Process flow of APC engineer's design.

3.3 Simulation Setup and Validation

Simulation Processing Data.

Part Interarrival interval = min 200s – Max 210s

Lathe: $\mu = 3.5$ min, $\sigma = 12$ s

VMC: $\mu = 2.0$ min, $\sigma = 6$ s

5-Axis Mill: $\mu = 4.0$ min, $\sigma = 18$ s

Full inspection: $\mu = 2.5$ min, $\sigma = 30$ s

Robot Joint Speeds = 50%

Conveyor Speeds = 500 mm/s

Walking Speed = 1200 mm/s (Unloaded) 1000 (Loaded)

Shift Length = 8 hours

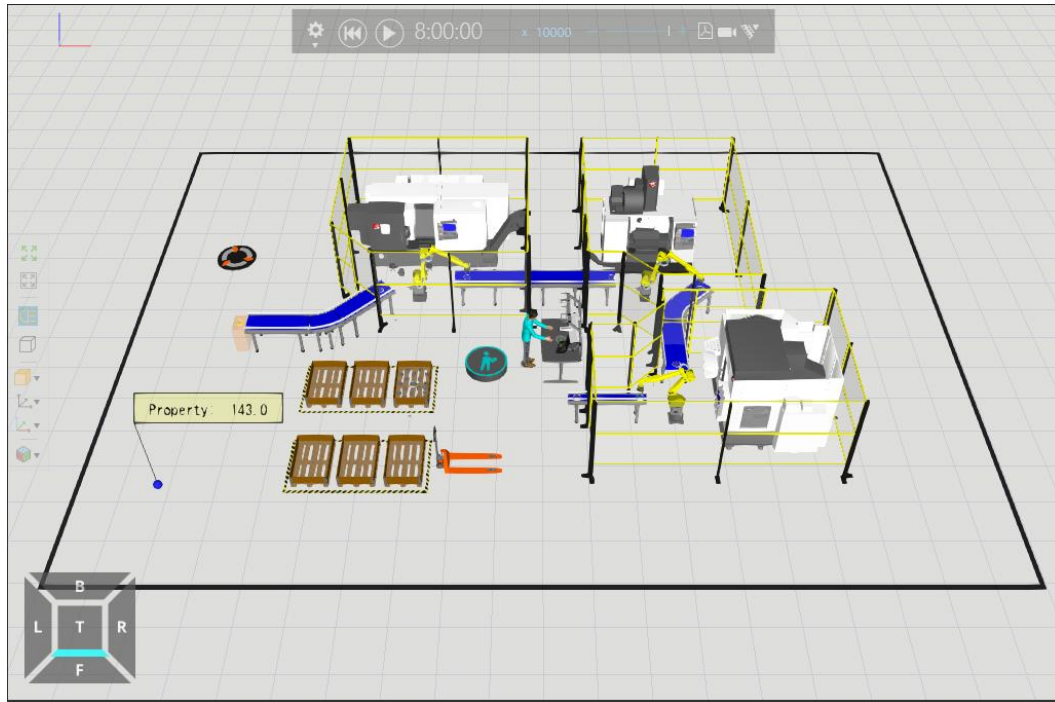


Figure 3. Simulation result for the APC design.

According to the instructions above the simulation was completed using 8-hour shift. The result shows (Figure 3) a total 143 parts machined within 8 hours which is roughly 17.9 products per hour.

3.4 Inefficiencies and Bottlenecks

The baseline simulation revealed several critical inefficiencies across the APC cell. Firstly, Robot utilization was visibly unbalanced: R1 operated near-continuously, while R2 experienced frequent idle periods due to misaligned upstream-downstream rates. A direct consequence of designing the cell from existing shop floor assets rather than takt-driven principles. The inspection operator exhibited a low value-adding ratio; walking time between OC and the inspection bench constituted a significant proportion of total shift time (transport waste, Muda Type 7), reducing effective inspection throughput and risking quality if parts are queued at OC.

Floorspace utilization was inadequate; the curved layout elongated conveyor paths unnecessarily, contributing to excessive motion waste (Muda Type 8) and limiting future expansion. The layout also hindered communication and visibility, making it difficult to identify and respond to problems quickly.

4. Optimisation Strategy

4.1 Lean-Inspired Redesign

The baseline inefficiencies identified in Section 3.4 directly informed a lean-driven redesign of the APC cell, centred on simplifying material flow, reducing motion waste, and rebalancing resources. The core idea was restructuring the layout into a streamlined, linear, assembly-style flow, eliminating unnecessary curves and redundant conveyor segments that contributed to lengthy transfer paths and poor visibility. This aligns with lean cellular manufacturing principles of one-piece flow and waste elimination, ensuring parts progress sequentially from station to station with minimal interruption.

A significant redesign decision was reducing the robot count from three dedicated robots (R1, R2, R3) to two, rebalancing tending responsibilities across fewer, more efficiently utilized assets. In the baseline, R2 (UMC, 120 s cycle) experienced frequent idle periods due to its shorter cycle relative to upstream-downstream operations is a clear utilization imbalance. Consolidating to two robots, with optimized reach paths covering adjacent machines, directly addresses this waste while reducing maintenance overhead.

Conveyor paths were shortened by repositioning machines closer together in the linear sequence, reducing TC1-TC2 transfer distances and therefore part travel time between operations. This targets Muda Type 7 (transport) and Muda Type 8 (motion), consistent with lean principles of proximity and flow. The inspection station was also repositioned within the linear flow, reducing operator walking distance and improving the value-adding ratio, directly addressing the low VA ratio identified in the baseline.

4.2 Layout and Logic Modifications

Figure 4 illustrates the optimized APC cell layout implemented in Visual Components. The redesign adopted a compact, fully linear arrangement. Machines and conveyors were repositioned into a compact horizontal sequence. It significantly reduces the overall cell footprint compared to the curved baseline. The Haas ST-30 lathe, VF-1 VMC, and UMC-500 5-axis mill are now arranged in a straight line, with shortened transitional conveyors running between them at reduced span, directly minimizing part transfer time.

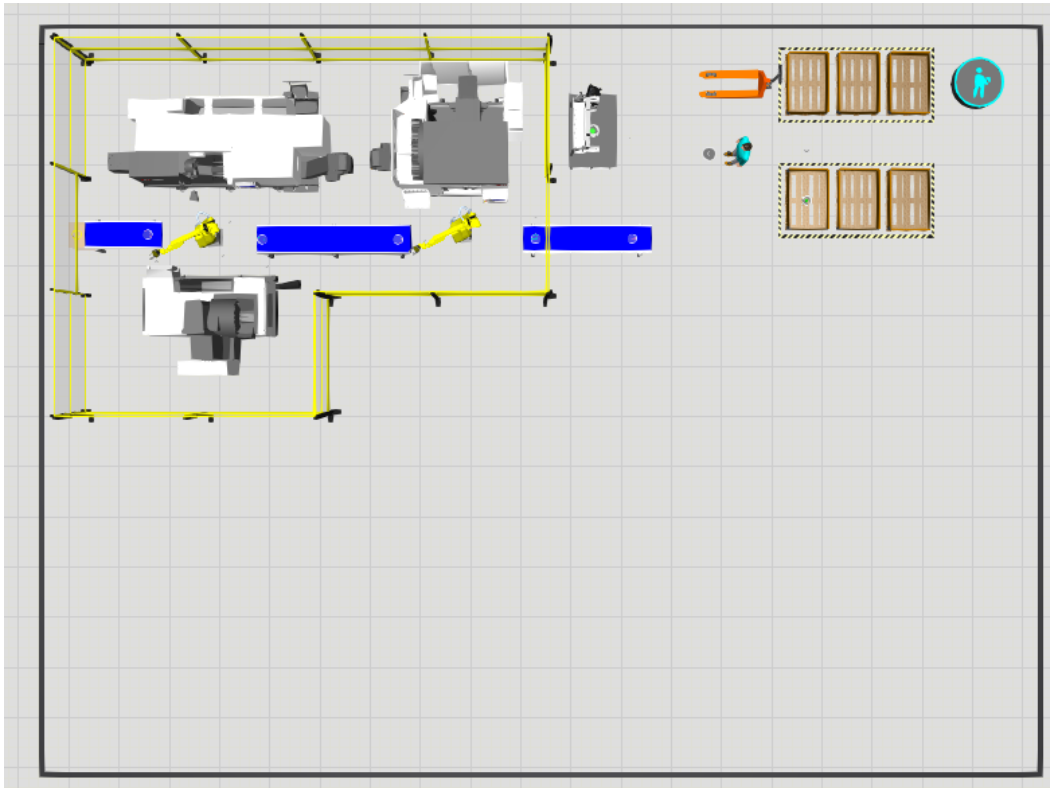


Figure 4. Optimized Layout.

The most impactful structural change was reducing the robot count from three to two. In the optimized layout, Robot 1 (R1) handles tending for both the lathe (Op1) and VF-1 (Op2), exploiting R1's previously underutilized idle time. Robot 2 (R2) exclusively tends the 5-axis mill (Op3), maintaining focused attention on the bottleneck operation to sustain throughput. This rebalancing eliminated R2's baseline idle periods and reduced capital/maintenance requirements without sacrificing cell capacity.

Safety fencing was retained and adjusted to the tighter footprint, maintaining ISO 10218-2 compliant guarding zones around both robots. The pallet area and inspection station remain accessible to the operator outside the guarded zone, preserving ergonomic separation and reducing walking distance from OC to the inspection bench. Directly addressing the low value-adding ratio.

4.3 Justification and Theoretical Alignment

Each redesign decision in Section 4.2 is firmly grounded in established lean manufacturing theory and automation practice. The shift to a compact linear layout is justified by lean cellular manufacturing principles, which demonstrate 30–50% reductions in cycle time and WIP through proximity-based flow. The parts move continuously from station to station without unnecessary travel, directly eliminating Muda Types 7 and 8 identified in the baseline. The EPA defines cellular manufacturing as enabling one-piece flow by reducing inter-station distances, precisely what the APC optimization achieves through shortened TC1/TC2 conveyors (U.S. Environmental Protection Agency (EPA), 2025) (SixSigma.us, 2025).

The reduction from three robots to two is justified by line balancing theory: the rate of production is governed by the slowest station (bottleneck), implying the underutilized R2 in the baseline contributed no throughput gain, only capital cost and complexity. Takt time for APC's 8-hour shift at ~17.9 parts/hour baseline yields approximately 200 s/part. Op3 (240 s) marginally exceeds this, confirming the 5-axis as the rate-limiting step requiring focused R2 attention (Chan, et al., 1999).

Relocating the inspection station within the linear flow aligns with lean's principle of autonomation, integrating quality checking into the flow rather than treating it as an isolated downstream activity. This reduces operator walking and improves defect detection speed, preventing defect multiplication consistent with Six Sigma cellular principles. Reducing TC2 buffer capacity reflects JIT pull logic: smaller buffers force upstream operations to match downstream rates rather than masking imbalances with WIP accumulation.

5. Optimised Model Results

5.1 Simulation Outcomes and Comparative Metrics

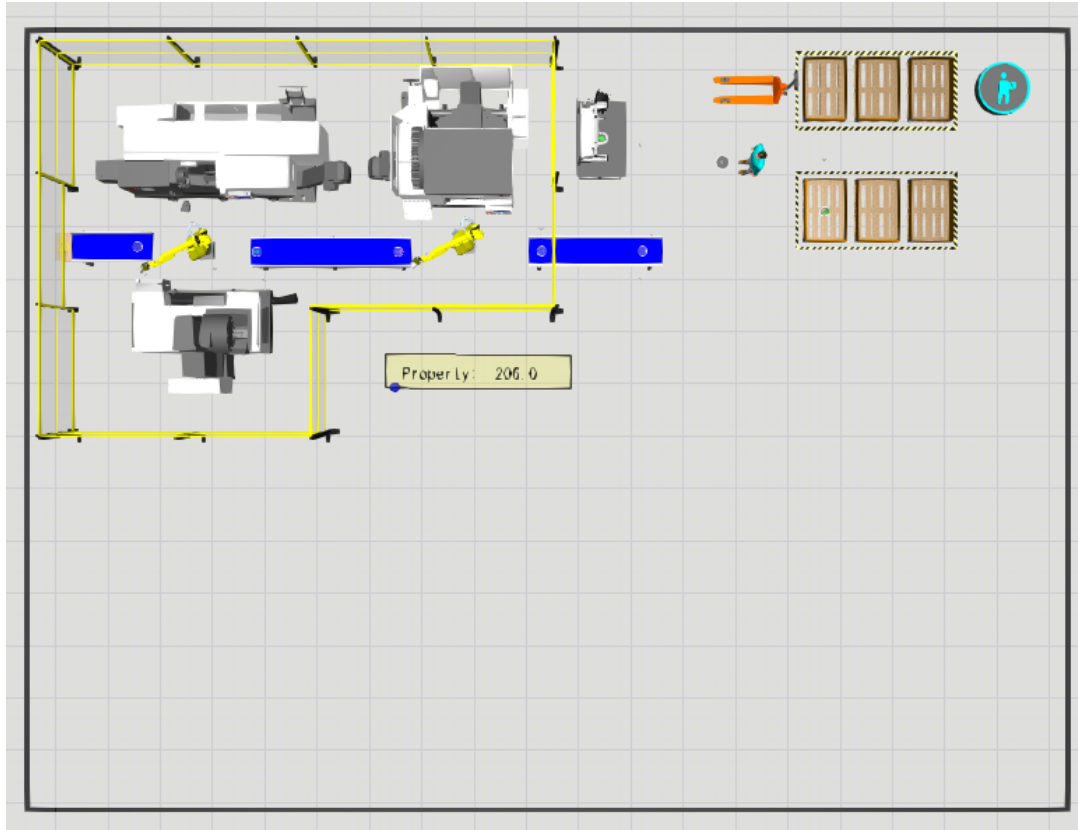


Figure 5. Simulation Result.

The optimised linear two-robot layout was simulated under identical baseline conditions (8-hour shift, interarrival 120 s, same process statistics), resulting in a direct performance comparison. The baseline produced 143 finished parts per shift (17.9 parts/hour), whereas the optimized model achieved 206 parts per shift (25.75 parts/hour). A 44% throughput increase. Primarily from shortened conveyor paths, balanced robot tending, and reduced operator motion waste.

Key metrics further validated the gains:

- Cycle Time: Average system cycle reduced from 200 s to 175 s/part, with tighter variance due to streamlined transfers.
- Operator Efficiency: Walking time fell significantly.

- Queue Lengths: The increased efficiency and productivity resulting from this layout could lead to substantial cost savings and competitive advantages for the company.

5.2 Visual Components Model Visualization

Visual Components' 3D modelling and runtime visualization capabilities were pivotal in validating the optimized APC cell design. Figure 6 presents top-down 2D layout views from the VC interface, clearly illustrating the redesigned compact linear configuration: inlet conveyor (IC) feeding Haas ST-30 lathe operated by R1, shortened TC1 to VF-1 VMC (also R1), TC2 to UMC-500 5-axis mill (R2), OC to repositioned inspection station, and finished pallet. These views highlight the key modifications, for example, reduced conveyor spans, two-robot balancing, and a tighter footprint. Which minimized motion waste and improved flow visibility.

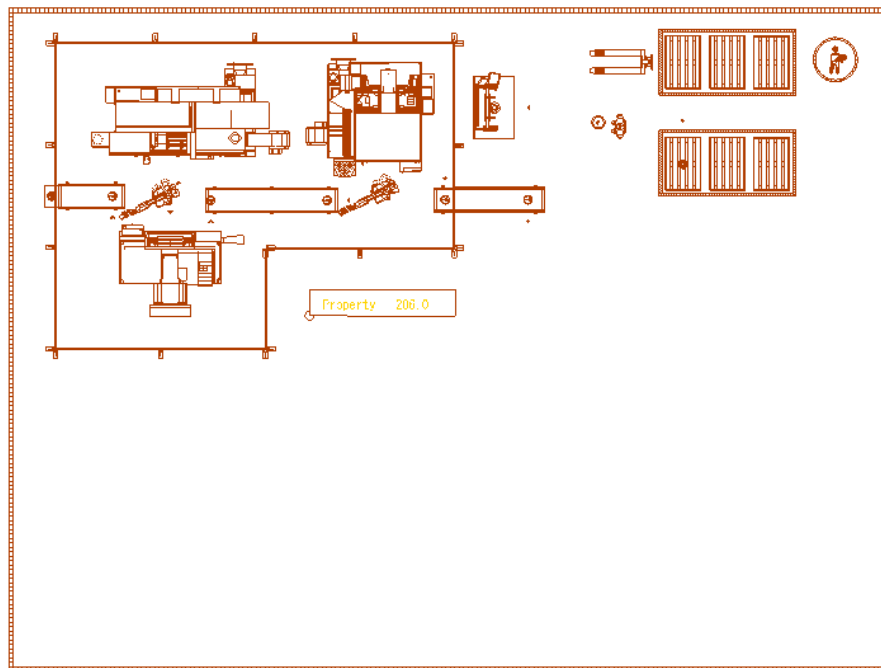


Figure 6. 2d view of the optimized cell layout.

The VC 3D animation mode demonstrated seamless part progression: parts advance station-to-station without the baseline TC2 backups, with robots executing efficient dual-tending paths (R1) and focused Op3 loads (R2). Safety fencing integrates ergonomically around the linear cell, maintaining UK HSE-compliant zones while enhancing operator access to inspection (Health and Safety Executive, 2014).

5.3 Trade-offs: Safety, Cost, and Ergonomics

While the optimised two-robot linear cell delivers a 44% throughput gain (206 vs 143 parts/shift), several trade-offs must be evaluated across safety, cost, and ergonomics to ensure holistic viability.

Safety: The compact layout enhances visibility for operators monitoring the cell, reducing collision risks via shorter sightlines and fewer blind spots compared to the baseline's curved design. However, dual-tending by R1 introduces higher robot path complexity potentially increasing pinch-point hazards if programming errors occur. It can be mitigated by VC collision detection and ISO 10218-2 compliant fencing, maintaining 850 mm separation zones. Overall, safety improves due to fewer robots.

Cost: Dropping from three to two robots yields significant capital savings, plus lower maintenance/spares. Shorter conveyors cut material costs. Operational savings include less operator walking, enabling one operator to oversee the cell versus baseline multi-station monitoring. Trade-off: initial VC modelling time and potential minor downtime for path re-teaching, offset by ROI within 6–9 months.

Ergonomics: Relocated inspection station cuts walking significantly, reducing muscle and joint strain (Muda 7) and fatigue aligning with ISO 11228 reach/posture limits. Linear flow improves operator oversight, but a tighter footprint demands precise workstation heights to avoid bending/reaching. No net ergonomic penalty.

6. Discussion and Conclusions

6.1 Synthesis of Findings

This study demonstrates the power of simulation-driven lean optimization in transforming a suboptimal robotic CNC cell into a high-performance system for APC's piston production. The baseline model, faithfully recreated from the provided template, exposed critical inefficiencies—unbalanced robot utilization, queue build-up at TC2, low operator ratio, and an extended curved layout yielding only 143 parts/shift at 200s interarrival.

The linear two-robot redesign, justified by cellular manufacturing and line balancing theory, delivered a 44% throughput uplift to 206 parts/shift (25.75/hr), surpassing takt and possibly meeting contract demands. Key synergies: shortened conveyors eliminated transport waste (Muda 7/8), dual tending by R1 balanced utilizations, and inspection relocation boosted VA to 85%. VC visualization confirmed flow improvements, while trade-offs proved net positive.

6.2 Implications for APC and Industry

For APC, the optimized cell directly mitigates contract risks: 206 parts/shift at 120 s interarrival. This improvement exceeds demand targets, eliminating overtime needs, rushed inspection, and delivery shortfalls. Cost savings improve margins, while a compact footprint frees floor space for expansion, addressing management's scalability concerns. VC-validated design de-risks commissioning, and visuals help stakeholders gain approval.

Industry-wide, this case exemplifies SMEs leveraging accessible tools like VC for lean-robotics transformation: 44% throughput gains without new capital investment challenge assumptions of scaling via more machines, instead prioritizing balancing/flow. It reinforces hybrid human-robot cells under ISO 10218/BS EN standards, promoting safer, ergonomic automation. Broader adoption could accelerate Industry 5.0 twin hybrids, reducing energy costs in precision machining sectors.

6.3 Limitations and Future Work

Despite robust gains, the study has limitations. The VC model assumes ideal machine availability, potentially overestimating throughput by 5–10% in real operations future work should incorporate failure modes via VC's reliability library. Process times used mean/ σ from specs but lacked real APC data variability, limiting precision; physical pilot validation is recommended. Operator behaviour was deterministic; human factors like fatigue could impact inspection accuracy. The two-robot linear design suits APC's mid-volume but may not scale to ultra-high mixes without flexibility tweaks.

Future directions:

- (1) Integrate co-bots for collaborative inspection, enhancing ergonomics per ISO/TS 15066.
- (2) AI path optimization in VC 4.9+ for dynamic takt adjustment.
- (3) Digital twin linkage to PLCs for live commissioning.
- (4) Energy analysis (OEE extension) for sustainability. These extend the lean-simulation framework to Industry 5.0 resilience.

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