

Modelling & Optimisation of Automated Manufacturing Processes

Abstract

This study investigates the application of simulation-driven process design and optimisation to an automated robotic machine-tending operation using Visual Components. The work aims to develop an advanced understanding of how digital simulation can identify and address inefficiencies related to layout configuration, resource utilisation, equipment effectiveness, and process flow within an automated system. The initial model is critically analysed to detect sources of waste and performance constraints, after which a series of simulation-based experiments are conducted to evaluate alternative configurations and control strategies. Lean manufacturing principles and established automation best practices guide the optimisation process, ensuring that proposed improvements enhance operational efficiency while maintaining safety and compliance requirements. The resulting optimised system design demonstrates how simulation tools can support evidence-based decision making, reduce integration risk, and enable continuous improvement in automated manufacturing environments.

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1. Introduction

The increasing complexity of modern manufacturing systems has intensified the need for robust digital tools capable of supporting process design, optimisation, and decision making. As organisations continue to adopt automation and robotics to improve productivity, consistency, and safety, simulation technologies have become essential for evaluating system performance prior to physical implementation. Among these tools, Visual Components offers a powerful platform for modelling automated production processes, conducting virtual experiments, and analysing system behaviour under varying conditions.

Machine-tending operations, which typically involve robotic loading, unloading, and handling of components, represent a critical application area where simulation can provide substantial value. Such systems often suffer from inefficiencies related to poor layout design, uneven resource utilisation, excessive machine idle time, bottlenecks, and non-optimised material flow. Without rigorous analysis, these inefficiencies can lead to reduced operational performance, increased production costs, and unnecessary downtime.

Simulation-driven process design is increasingly recognised as a key enabler of lean manufacturing, providing a means to identify waste, validate improvement strategies, and optimise equipment interactions within a virtual environment. By integrating lean principles with automation best practices, it becomes possible to explore alternative system configurations, test process adjustments safely, and develop solutions that enhance both efficiency and compliance.

This study applies these concepts to an automated robotic machine-tending system, using Visual Components to model, analyse, and optimise its performance. Through systematic experimentation and critical evaluation, the work aims to demonstrate how simulation can support continuous improvement, reduce integration risks, and facilitate evidence-based decision making in advanced manufacturing environments.

2. Literature Review

Simulation-driven process design has become a fundamental component of modern manufacturing engineering, particularly as organisations continue to adopt automated systems and robotics to enhance efficiency, resilience, and competitiveness (Castiglione, Cimmino, Di Nardo, & Murino, 2024). The increasing complexity of production environments, characterised by high product variety, shorter lead times, and stringent quality requirements, has elevated the importance of digital tools capable of modelling, analysing, and optimising system performance prior to physical implementation (Zhang, Zhou, Ren, & Laili, 2019).

Research across robotics, automation, digital manufacturing, and lean engineering consistently highlights the value of simulation in identifying inefficiencies, supporting data-driven decision making, and enabling safer, more efficient system integration. This literature review explores key themes relevant to simulation-driven optimisation of robotic machine-tending operations, including current developments in robotics and automation, integration methodologies, lean principles, digitalisation trends, and regulatory considerations.

2.1 Robotics and Automation in Modern Manufacturing

Industrial robotics has evolved significantly, transitioning from isolated, high-volume applications to more flexible, intelligent, and collaborative systems capable of addressing complex manufacturing needs. Traditional industrial robots were primarily designed for repetitive, high-speed tasks within structured environments (Liu, Liu, Xu, Wang, & Zhou, 2022). However, contemporary research emphasises advanced sensing, improved manipulators, machine vision integration, and AI-based motion planning as mechanisms enabling robots to operate in more dynamic environments and handle variable component types. As product diversity continues to increase, automation systems must support faster reconfiguration and greater adaptability, which in turn amplifies the role of virtual modelling in system design (Li, Li, Li, & Liang, 2025).

In machine-tending operations specifically, the robot's performance is influenced by factors such as path optimisation, tool configuration, cycle time alignment with machines, and workstation layout. Research indicates that small deviations in these variables such as suboptimal design, unnecessarily long travel distances, or mismatched process times, can lead to significant inefficiencies. Consequently, simulation tools provide a valuable method for evaluating and refining robotic operations without disrupting production (Hofmann & Wenzel, 2020).



Figure 1 – Robots in Modern Manufacturing (Wasim, 2023)

2.2 Simulation Driven Process Design

Simulation-driven process design has emerged as a critical method for assessing manufacturing system performance. It enables engineers to create digital models that replicate the behaviour of physical systems, test alternative configurations, and analyse the effects of process modifications. Virtual models offer the advantage of allowing “what-if” experimentation, where cycle times, robot trajectories, equipment layouts, resource scheduling, and control logic can be modified to evaluate potential improvements (Pajpach, Pribis, Drahos, Erik, & Haffner, 2025).

Discrete event simulation (DES), which focuses on modelling systems where state changes occur at discrete points in time, is widely used for evaluating production performance. In contrast, 3D simulation platforms such as Visual Components extend beyond DES capabilities by representing the physical motion, reachability, and interactions of robots and machines. This offers richer insight into spatial constraints, collision risks, safety zones, and ergonomic considerations (Trebuna, Pekarcikova, Duda, & Svantner, 2023).

Simulation-driven approaches also support the identification of bottlenecks, which often occur when system resources are not synchronised or adequately balanced. Examples include uneven task durations between multiple CNC machines, robots experiencing idle time while waiting for machine availability, or excessive queuing due to inefficient buffer design. Through simulation, engineers can systematically adjust process variables, evaluate alternative configurations, and quantify the effect of changes on efficiency, throughput, and machine utilisation (Soliman, 2024).

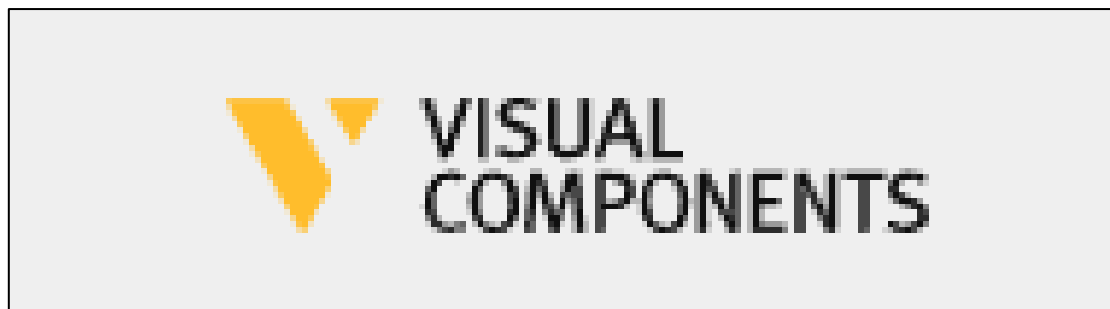


Figure 2 – Visual Components

2.3 Lean Manufacturing Principles and Waste Reduction

The integration of lean manufacturing principles with simulation-based optimisation has gained increasing academic and industrial attention. Lean approaches prioritise the elimination of non-value-adding activities, commonly referred to as the “7 Wastes” these include defects, overproduction, waiting, transportation, inventory, motion, and over-processing. In automated systems, common forms of waste include excessive robot movement, machine idle time, poorly located equipment, excessive handling steps, and unnecessary buffers (Brad & Deeb, 2025).



Figure 3 – The 7 Wastes (Collins, 2021)

Simulation supports lean initiatives by offering a platform in which waste can be visualised, quantified, and systematically removed. For instance, robot-movement waste can be reduced by optimising trajectories, repositioning machines, or redesigning the cell layout. Waiting waste may be addressed by balancing cycle times between machines, adjusting robot speeds, or implementing parallel robotic operations (McGarry, 2025). The literature shows that simulation provides a rigorous means of validating lean strategies before implementation, thereby reducing trial-and-error costs and ensuring that improvements are both feasible and sustainable.

Value stream mapping (VSM), a fundamental lean tool, is frequently enhanced through simulation, allowing digital verification of future-state designs. By incorporating simulation data, engineers gain deeper insight into the dynamic interactions between resources, thereby enabling more accurate predictions of system behaviour under varying conditions (Jarkko, Lu, Lars, & Thomas, 2013).

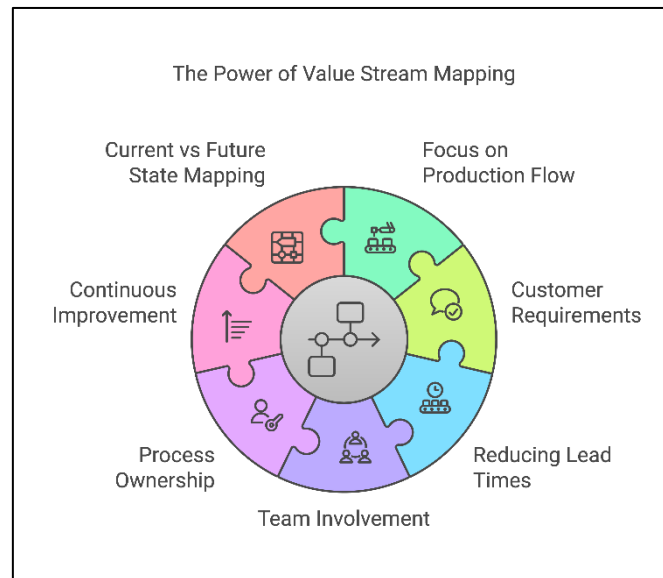


Figure 4 – Value Stream Mapping (Ayers, 2026)

2.4 Integration of Robots and Automated Systems

Robotic integration within manufacturing environments requires coordination between hardware, software, controls, communication interfaces, and safety mechanisms. The literature identifies several key challenges in robotic system integration such as interoperability, safety compliance, communication latency, and human–robot interaction.

2.4.1 Interoperability and Control Architectures

Interoperability remains a major barrier to seamless automation, particularly in environments where robots must coordinate with CNC machines, conveyors, sensors, and programmable logic controllers (PLCs). Standardised communication protocols such as Open Platform Communications (OPC), Unified Architecture (UA), Message Queuing Telemetry Transport (MQTT), and industrial Ethernet variants which allow consistent data exchange across varied systems (Freitas, et al., 2024). The adoption of modular and open control architectures reduces integration effort and facilitates scalability, with platforms enabling more flexible robot programming and coordination (Seo, Paik, & Yim, 2019).

2.4.2 Human-Robot Collaboration

As human operators continue to work alongside robots in manufacturing, system design must incorporate ergonomic and safety considerations. Collaborative robots (cobots) have become widely studied due to their ability to operate without full physical barriers, enabling shared workspaces. Research emphasises that cobots must adhere to defined safety functions such as speed-and-separation monitoring, power-and-force limiting, and real-time environment sensing (Anandan, 2016). Simulation is often used to verify collaborative workspaces, establish safety envelopes, and test interactions prior to implementation.



Figure 5 – Collaborative Robots (Hollinger, 2016)

2.4.3 Virtual Commissioning

Virtual commissioning is an increasingly important step within integration. It involves testing control logic, PLC programs, robot routines, and safety interlocks inside a digital model before deploying them to physical equipment. This practice reduces commissioning time, lowers integration risks, and avoids potentially costly equipment damage. The literature highlights that virtual commissioning bridges the gap between design and operation by enabling engineers to test fault scenarios, refine timing, and identify coordination issues early (SIEMENS, 2026). Simulation plays a critical role in meeting safety requirements by allowing engineers to verify robot reachability, ensure adequate safety distances, and test safeguarding functions without exposing personnel to risk. Virtual models can be used to validate the placement of emergency stops, light curtains, guarding, and safety-rated monitored stops. This reduces the likelihood of safety non-compliance during physical installation (Finaro, Greenberg, & Carlson, 2023).

2.5 Digitalisation and Industry 4.0 Trends

The digital transformation of manufacturing has accelerated the adoption of advanced technologies such as digital twins, cyber-physical systems (CPS), and Industrial Internet of Things (IIoT) platforms. These technologies integrate cyber (digital) and physical elements to enable real-time monitoring, predictive analytics, and closed-loop optimisation (Lin, et al., 2021).



Figure 6 – Industrial Internet of Things (Smith, 2018)

2.5.1 Digital Twins

Digital twins extend traditional simulation models by maintaining a continuous link to live operational data. This allows the virtual model to replicate, predict, and optimise real system behaviour in real time. For robotic operations, digital twins can help predict maintenance requirements, monitor robot health, evaluate deviations from expected performance, and support adaptive planning (Wang, Zhao, Lu, Zhang, & Lu, 2025).

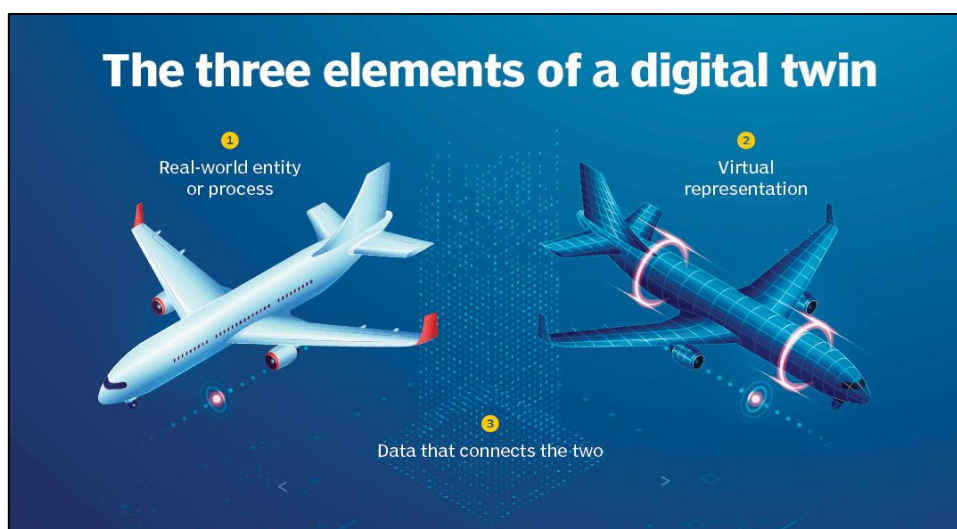


Figure 7 – Digital Twin (Shacklett, 2025)

2.5.2 Cyber-Physical Production Systems

Cyber-Physical Production Systems (CPPS) architectures integrate sensors, actuators, software, and network communication to create intelligent systems capable of autonomous decision-making. CPPS enabled machine-tending operations can dynamically adjust robot speeds, respond to machine availability, or optimise scheduling without human intervention. Simulation provides a test environment for validating algorithms and ensuring system safety (Thiede, 2021).

2.5.3 Data-Driven Support

The literature increasingly emphasises the value of integrating simulation with real-time production data, enabling predictive analytics, scenario testing, and performance tracking. Machine learning algorithms are being integrated into simulation pipelines to support automatic layout optimisation, anomaly detection, and cycle time prediction. Although still emerging, these approaches demonstrate the future potential of simulation-driven optimisation as a continuous improvement tool rather than a one-off design activity (Horr & Drexler, 2025).

2.6 Standards & Regulations

The design, integration, and operation of automated and robotic manufacturing systems are governed by a combination of statutory regulations and internationally recognised standards. These frameworks are essential for ensuring that automation systems operate safely, reliably, and in compliance with legal requirements. Within simulation-driven process design, early consideration of standards and regulations is critical, as it enables compliance to be embedded into system layouts, control strategies, and operational procedures before physical implementation (Sagova, Klackova, Kuric, & Tlach, 2025). This section outlines the key regulatory and standards-based frameworks relevant to automated robotic systems, clarifies the distinction between standards and regulations, and discusses the concept of compliance within an industrial context.

2.6.1 Distinction Between Regulations & Standards

Regulations and standards serve complementary but distinct roles within industrial governance.

Regulations are legally enforceable requirements established by governmental authorities. Compliance with regulations is mandatory, and failure to meet regulatory obligations can result in enforcement action, legal penalties, or operational restrictions. Regulations define minimum acceptable levels of safety and place legal duties on employers, equipment owners, and system integrators (Health and Safety Executive, 2025).

Standards, by contrast, are technical specifications developed by recognised bodies such as the International Organisation for Standardisation (ISO) and the International Electrotechnical Commission (IEC). While standards are not legally binding in themselves, they represent agreed best practice and are widely used as benchmarks for safe and effective system design. In practice, standards often become effectively mandatory when referenced by legislation, required by regulators, or incorporated into contractual agreements (ISO, 2026).

The relationship between regulations and standards is therefore symbiotic: regulations define what must be achieved, while standards describe how it can be achieved.

Aspect	Process Compliance	Process Adherence
Definition	Governed by external regulations and legal requirements	Governed by internal rules and policies set by the organisation
Authority	Regulated by external entities (e.g., government bodies)	Managed internally by the organisation
Legal Requirements	Includes legally mandated regulations with civil and criminal penalties for non-compliance	Based on internal guidelines that are not legally required
Focus	Compliance with external standards and regulations	Compliance with internal procedures and standards
Activities	Involves adherence to laws, external audits, and regulatory reporting	Includes internal audits, employee training, and adherence to corporate policies

Figure 8 – Regulations & Standards (Davies, 2026)

2.7 International Standards for Robotic Automation

2.7.1 ISO 10218 – Safety of Industrial Robots

ISO 10218 is the principal international standard governing the safety of industrial robots and robotic systems. It defines safety requirements for both robot manufacturers and system integrators, including safeguarding, emergency stop functionality, safety-rated control systems, and risk assessment procedures. In automated machine-tending operations, ISO 10218 informs cell layout design, access control, and protective measures, ensuring that hazards associated with robot motion and interaction are adequately controlled (ISO, 2025).

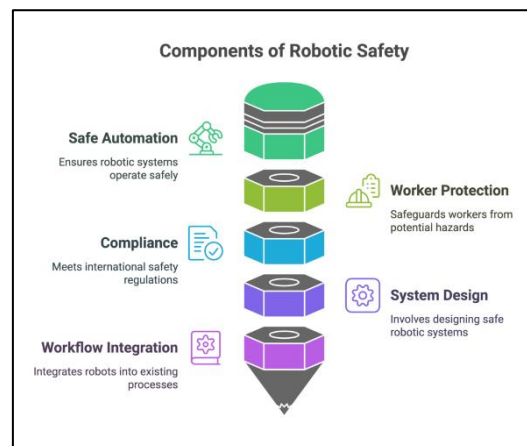


Figure 9 – ISO 10218 (Process Compliance: Importance, Benefits & More, 2026)

2.7.2 ISO/TS 15066 – Collaborative Robot Applications

ISO/TS 15066 supplements ISO 10218 by addressing collaborative robot applications in which humans and robots operate within shared workspaces. It defines recognised collaborative operating modes and provides biomechanical limits for human–robot contact forces. This standard is particularly relevant where operators interact directly with robotic systems, such as during part loading, unloading, or intervention tasks (ISO, 2025).

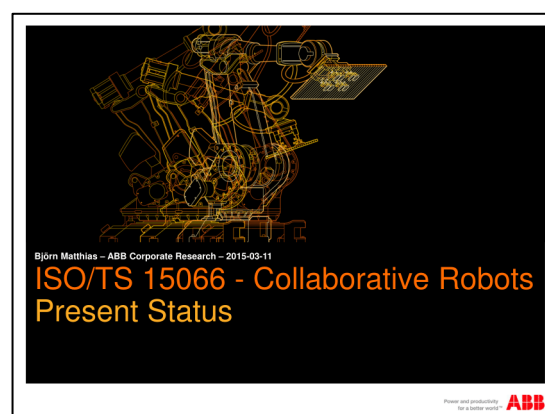


Figure 10 – ISO/TS 15066 (Matthias, 2015)

2.7.3 IEC 61508 – Functional Safety

IEC 61508 establishes requirements for the functional safety of electrical, electronic, and programmable electronic systems. It provides a framework for the design and validation of safety-related control systems, including emergency stops, light curtains, and interlocking devices. Compliance with IEC 61508 ensures that safety functions perform reliably under both normal and fault conditions (IEC 61508: The Functional Safety Standard, 2026).

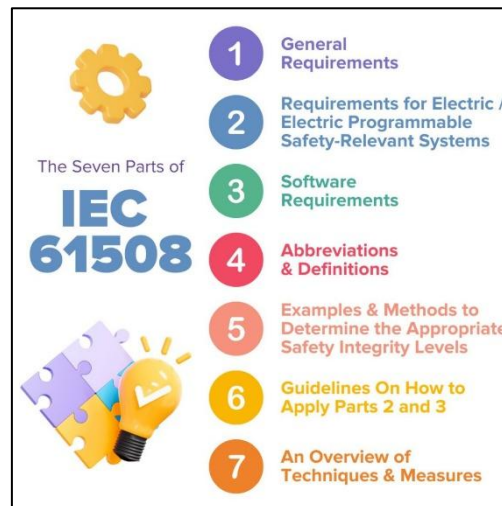


Figure 11 – IEC 61508 (Functional Safety Made Simple: A Guide to IEC 61508 for Manufacturing, 2026)

2.8 UK Regulatory Framework

2.8.1 Health and Safety at Work etc. Act 1974

The Health and Safety at Work Act 1974 (HSWA) is the primary legislation governing workplace health and safety in the UK. It imposes a general duty on employers to ensure, so far as is reasonably practicable, the health, safety, and welfare of employees and others affected by work activities. In automated manufacturing environments, HSWA requires employers to provide safe plant and equipment, safe systems of work, appropriate training, and effective supervision (Lanjewar, 2025).

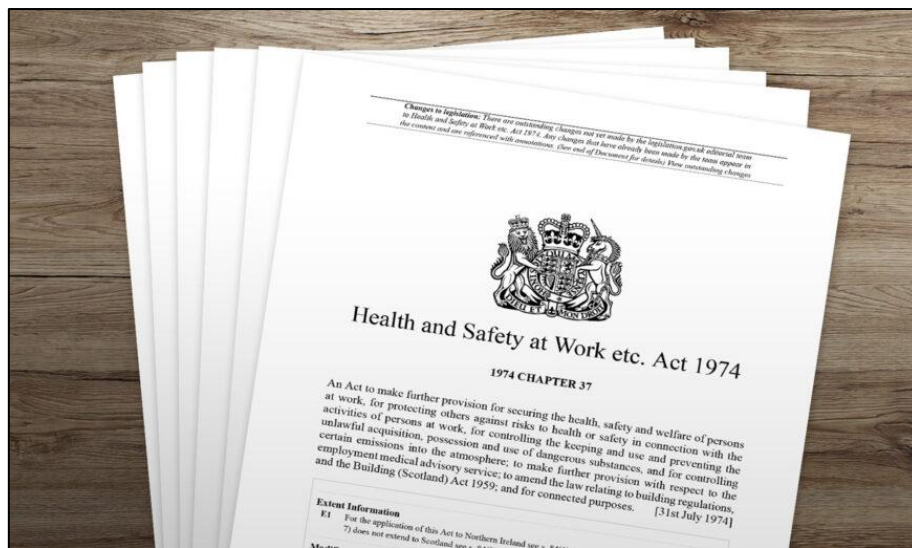


Figure 12 – Health and Safety at Work Act 1974 (James, 2024)

2.8.2 Provision and Use of Work Equipment Regulations 1998 (PUWER)

PUWER places specific duties on employers regarding the suitability, maintenance, inspection, and safe use of work equipment, including machinery and robotic systems. It requires that equipment be fitted with appropriate safeguards, emergency stops, and control systems, and that it is operated only by competent personnel. PUWER is directly applicable to robotic machine-tending systems and their associated equipment (Provision and Use of Work Equipment Regulations 1998 (PUWER) - overview, 2026).

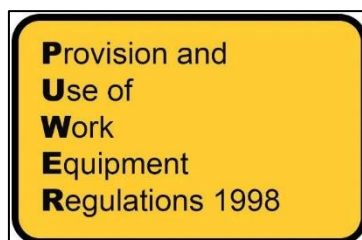


Figure 13 – PUWER (What Are The PUWER Regulations?, 2025)

3. Model Development

Alpha Precision Components (APC) is a Tier-1 supplier specialising in the manufacture of high-performance pistons for automotive and motorsport applications. As a Tier-1 supplier, APC operates within a highly demanding supply chain environment, where stringent requirements for quality, delivery reliability, and cost competitiveness must be consistently achieved. The company has recently secured a new contract to supply pistons for a turbocharged four-cylinder engine platform, requiring a rapid increase in production volume while maintaining extremely tight quality tolerances.

To support this contract, APC has designed a new automated piston machining cell comprising multiple CNC machining centres, industrial robots, conveyor systems, and a manual inspection station. However, the initial cell design was developed based primarily on existing shop-floor assets rather than through a structured optimisation approach. Early analysis raised concerns regarding insufficient throughput, unbalanced resource utilisation, excessive work-in-progress (WIP), and low value-adding efficiency of the inspection operator.

This report presents a structured analysis of APC's initial machining cell using discrete-event simulation in Visual Components. The study evaluates baseline performance, identifies key system inefficiencies, and proposes a redesigned solution based on lean manufacturing and automation principles. Quantitative performance comparisons are used to justify the proposed improvements and assess any associated trade-offs.

3.1 Initial Cell Layout

The initial machining cell implemented by Alpha Precision Components is arranged in a linear, functionally oriented layout and comprises three sequential CNC machining operations supported by dedicated industrial robots and conveyor-based material handling systems, this is shown in figure 14.

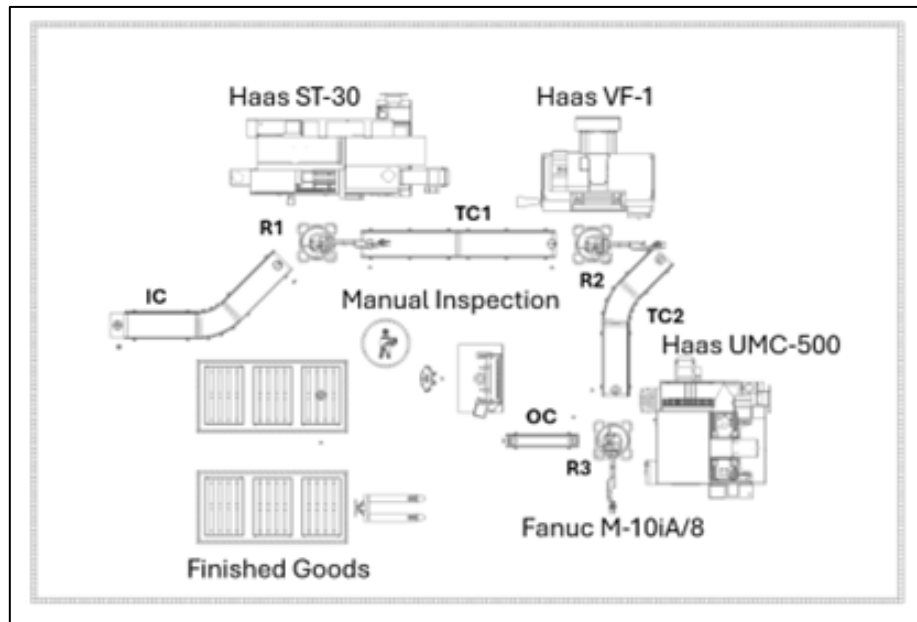


Figure 14 – Initial Cell Layout Sketch

The first stage of the process involves external and internal turning of raw piston blanks using a Haas ST-30 CNC lathe, with part handling fully automated via a Fanuc M-10iA/8L industrial robot, labelled 'R1' in figure 14, that loads components from the inlet conveyor (IC) and unloads machined parts onto an intermediate transitional conveyor (TC1).

The second stage consists of milling operations carried out on a Haas VF-1 vertical machining centre, where flats are machined and holes are drilled and tapped. The component transfer between operations is facilitated by a second dedicated Fanuc M-10iA/8L robot, labelled 'R2' in figure 14, which loads parts from the first transitional conveyor into the VMC and subsequently unloads completed components onto a second transitional conveyor (TC2).

In the final machining stage, critical piston features, are finished using a Haas UMC-500 five-axis machining centre, with a third dedicated robot, labelled 'R3' in figure 14, responsible for loading parts from the second transitional conveyor (TC2) and unloading finished components onto the outlet conveyor (OC).

Upon completion of all automated machining processes, components are collected from the outlet conveyor by a human operator and subjected to manual inspection at a dedicated workstation prior to placement onto finished goods pallets.

Figure 15 shows that whilst this configuration provides a clear and logically sequenced material flow that simplifies commissioning and control, it reflects a conventional push-based automation strategy in which intermediate conveyors act as decoupling buffers between operations.

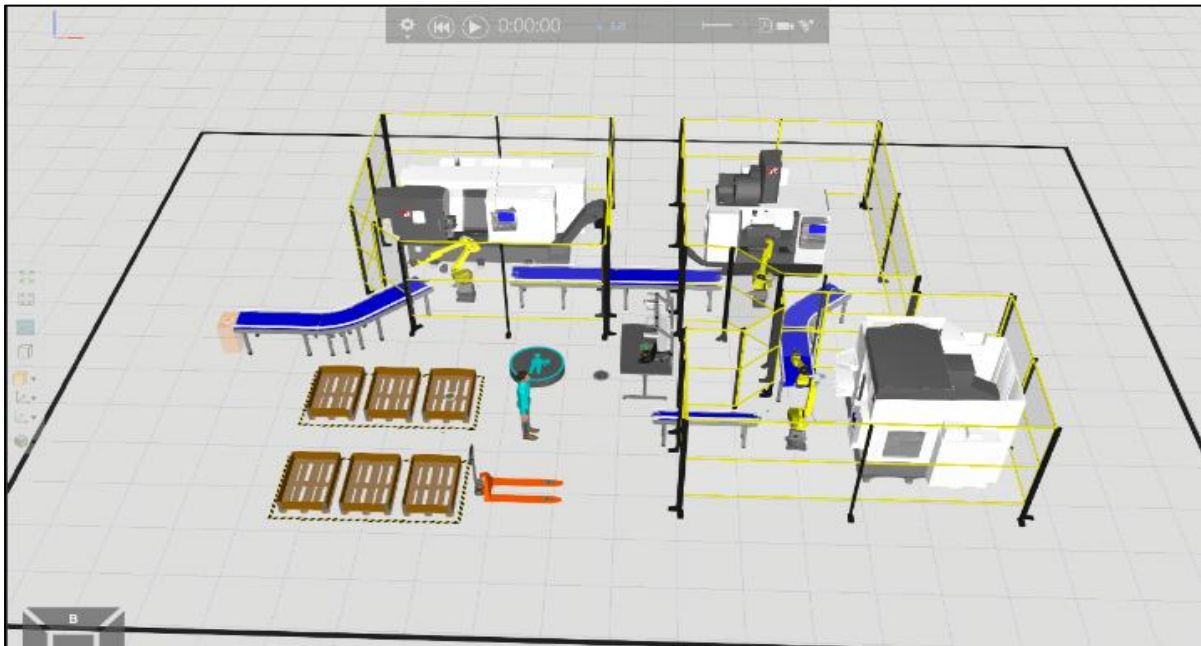


Figure 15 – Initial Cell Layout Visual Components

From a manufacturing systems perspective, this design prioritises local machine autonomy over global flow optimisation, resulting in increased work-in-progress, reduced responsiveness to downstream constraints, and a heightened risk of bottleneck-driven blocking and starvation.

Figure 16 presents the utilisation percentages of each machine within the original machining cell. The Haas UMC-50 demonstrates the highest level of utilisation at 95%, indicating that it is the most effectively used resource in the system. In comparison, the Haas ST-30 operates at 87% utilisation, while the Haas VF-1 records the lowest utilisation value at 50%.

The processing sequence of components within the cell is fixed and cannot be altered, meaning the machine order cannot be rearranged to improve utilisation through rotational optimisation. The relatively low utilisation of the Haas VF-1 is primarily attributed to its longer processing time, which limits throughput and increases downstream waiting. Conversely, the Haas ST-30 performs efficiently, supported by the near-continuous arrival of parts and its ability to process them with minimal delay.

The Haas UMC-50 also maintains strong performance, with its high utilisation partly influenced by the presence of travel delay, which creates a longer interval before the next part arrives.

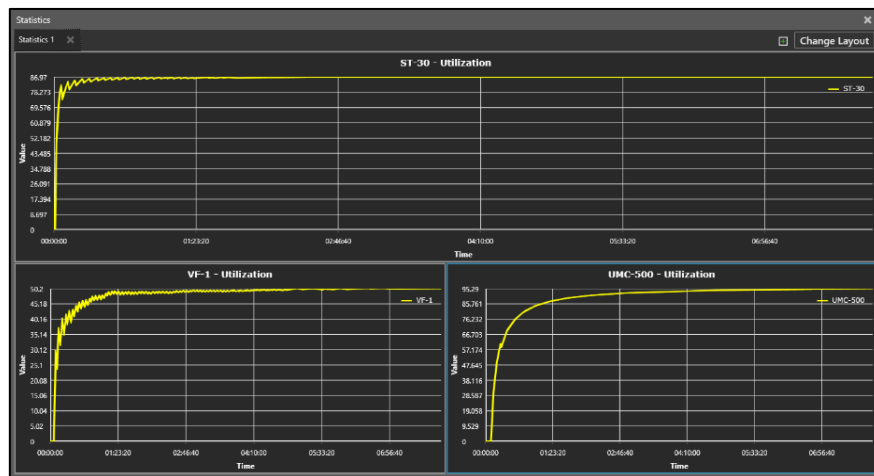


Figure 16 – Utilisation Values in Original Cell

Figure 17 illustrates the utilisation percentages of each machine within the redesigned cell layout. The Haas UMC-50 remains the most highly utilised resource, operating at 86% utilisation. In comparison, the Haas ST-30 achieves a utilisation percentage of 81%, while the Haas VF-1 records the lowest utilisation at 45%.

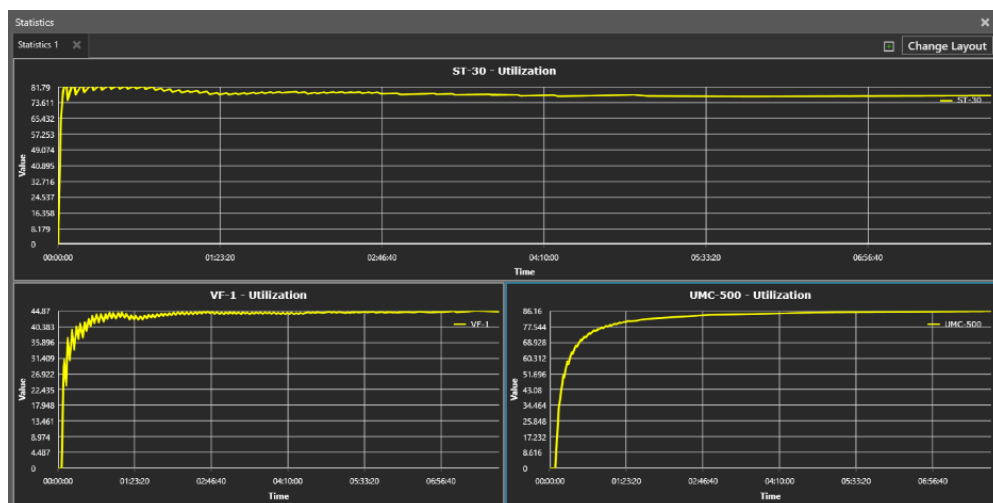


Figure 17 – Utilisation Values in Redesigned Cell

Overall, machine utilisation levels are reduced relative to the original layout. This decrease is attributed to the shorter conveyor travel distances, which reduce transfer time but increase idle and waiting time within the system. This effect is most strongly influenced by the second machining phase, carried out by the Haas VF-1, which continues to act as the primary bottleneck due to its longer cycle time. To achieve a substantial improvement in throughput, Alpha Precision Components (APC) would need to evaluate equipment investment options, such as replacing the Haas VF-1 with a higher-capacity alternative or introducing a secondary machine to operate in parallel with the existing unit. This approach would increase overall production capacity while maintaining consistent process

parameters, reducing the likelihood of additional setup time, extended trials, or increased defect rates. Additionally, support requirements such as consumables, spare parts, and maintenance practices could remain largely unchanged.

Consequently, although the cell is technically robust and straightforward to operate, it lacks inherent mechanisms for workload balancing and demand-driven control, limiting its ability to achieve high throughput and stable performance under variable processing conditions.

Figure 18 presents the number of parts processed within the original cell layout. Over an eight-hour shift, the system produces a total output of 101 parts.

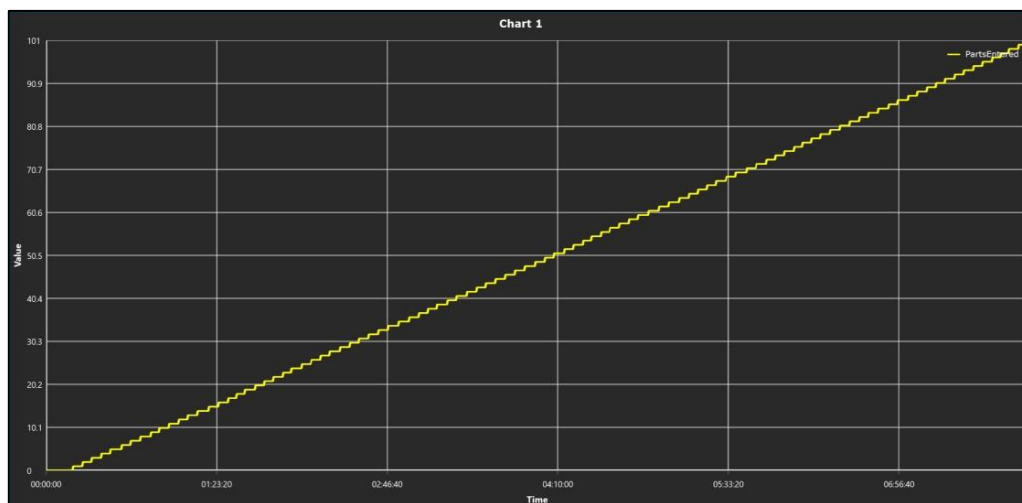


Figure 18 – Parts Processed in Original Cell

Whilst figure 19 shows the number of parts processed within the redesigned cell layout. A total of 111 parts are produced over an eight-hour shift, representing an increase of 10 parts compared to the original configuration. This corresponds to a 9.9% improvement in output.

The marginal increase in throughput is primarily attributed to a significant reduction in travel time, resulting in lower motion-related waste. This improvement is achieved through the revised arrangement of machines in closer proximity and the consolidation of tending operations under a single robot. As a result, the robot in the redesigned layout remains active for a greater proportion of the shift when compared to the three-robot arrangement used in the original cell. In the initial configuration, the robots experienced increased idle time due to extended travel distances and waiting periods while machines completed machining cycles before parts could be transferred to the conveyor.

A further contributing factor is the reduced travel distance within the new cell configuration, which improves transfer efficiency and supports higher overall part throughput. Subsequent figures provide a direct comparison of these travel differences between both layouts.

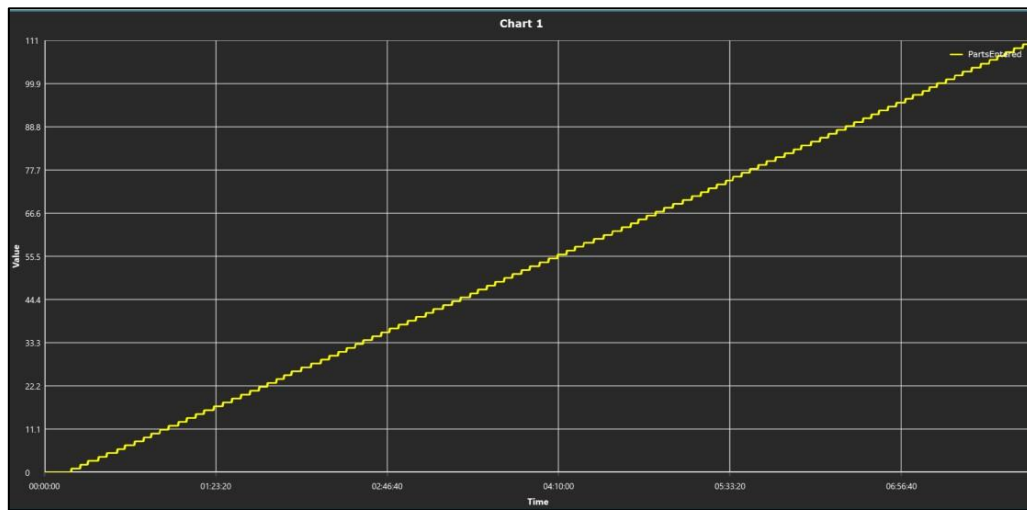


Figure 19 – Part Processed in Redesigned Cell

3.2 New Cell Layout

To optimise the initial machining cell layout, the three CNC machines were reconfigured into a compact circular arrangement and serviced by a single industrial robot responsible for tending all machining operations, this is clearly portrayed in figure 20. This redesign was implemented to address the inefficiencies associated with duplicated robotic resources and excessive material handling present in the original linear configuration.

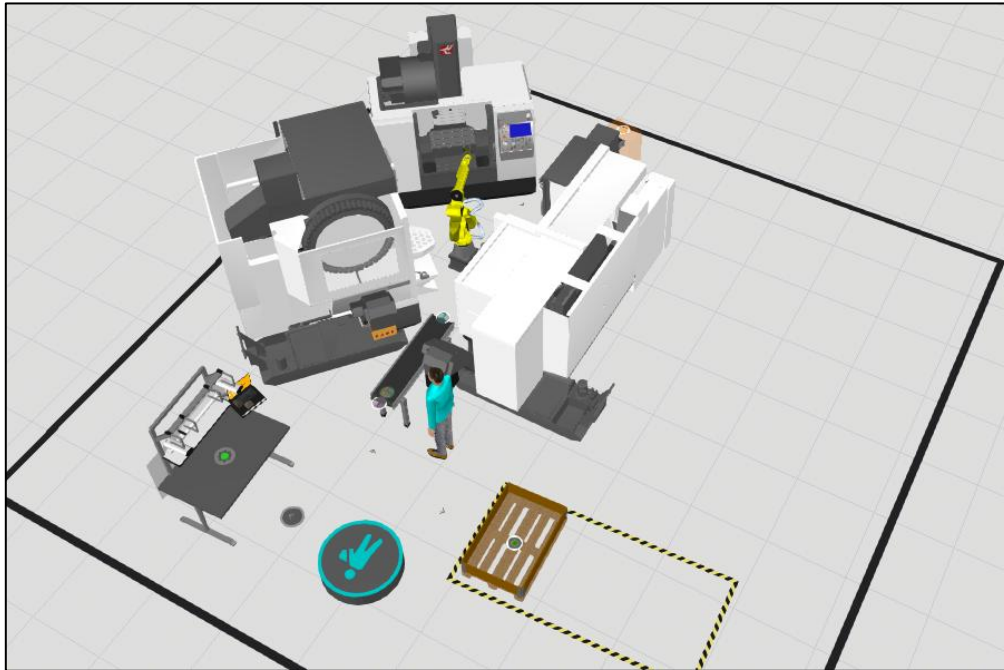


Figure 20 – Redesign of Cell Visual Components

By consolidating machine tending into a single robot, non-value-adding motion was significantly reduced, eliminating redundant pick-and-place operations and idle time associated with underutilised robots. In addition, the circular configuration enabled direct, short-range transfers between machines, thereby removing the need for multiple transitional conveyors and substantially reducing part transport time, buffering, and associated work-in-progress.

Figure 21 shows the operational states of the three machines within the original cell layout. The pie charts present the proportion of time each machine spends in the states of busy, idle, and blocked during an eight-hour shift. The Haas ST-30 operates in a busy state for 86.96% of the shift, remains idle for 12.11%, and is blocked for 0.93%. The Haas VF-1 records a busy time of 50.2% and an idle time of 49.8%, indicating substantial underutilisation. The final operation, the Haas UMC-500, demonstrates the highest machine activity, operating busy for 95.29% of the shift, idle for 4.22%, and blocked for 0.49%.

When considered collectively, the three machines exhibit a significant proportion of idle time across the process, representing non-value-added time and reduced operational efficiency. Over the eight-hour shift, the combined machine statistics show that the cell is busy for 77.48% of the time, idle for 22.04%, and blocked for 0.47%. The high level of idle time is a key performance limitation that Alpha Precision Components must address. The Haas VF-1 is identified as the primary contributor to this inefficiency due to its notably low busy time relative to the other machines.

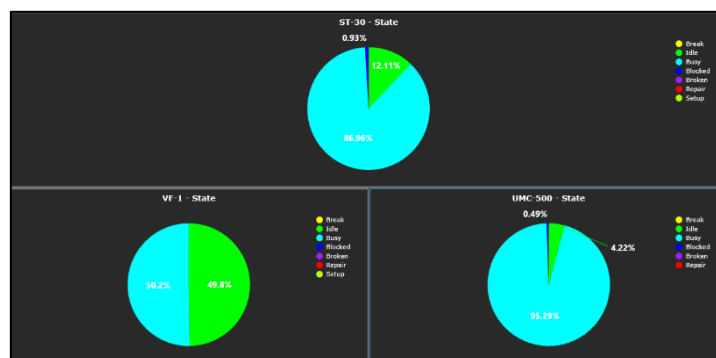


Figure 21 – State of Equipment in Original Cell

Figure 22 presents the operational states of the three machines within the redesigned cell layout. The pie charts illustrate the proportion of time each machine spends in the states of busy, idle, and blocked over an eight-hour shift. The Haas ST-30 operates in a busy state for 77.37% of the shift, remains idle for 14.5%, and is blocked for 8.13%. The Haas VF-1 records a busy time of 44.76%, an idle time of 16.69%, and a blocked time of 38.45%. The final operation, the Haas UMC-500, operates busy for 86.13% of the shift, idle for 10.87%, and blocked for 3%.

When considered collectively, the three machines demonstrate reduced idle time compared to the original cell configuration, indicating improved continuity of machine activity. Across the full eight-hour shift, the combined statistics show that the cell operates busy for 69.42% of the time, remains idle for 14.05%, and is blocked for 16.53%. While idle time has decreased, the increased proportion of blocked time suggests that flow constraints remain within the system, particularly in relation to the Haas VF-1, which exhibits the highest level of blocking among the three machines.

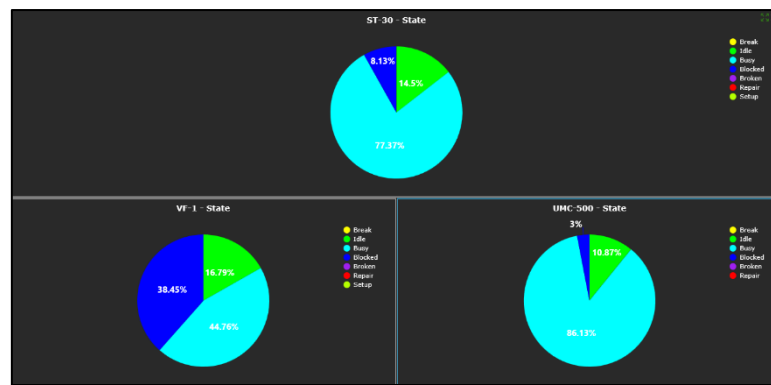


Figure 22 – State of Equipment in Redesign Cell

Figure 23, shows the cell from a layout efficiency perspective, the circular cell design improved floor space utilisation and enhanced spatial integration of resources, allowing the system to operate with a smaller footprint while maintaining clear machine access and visibility.

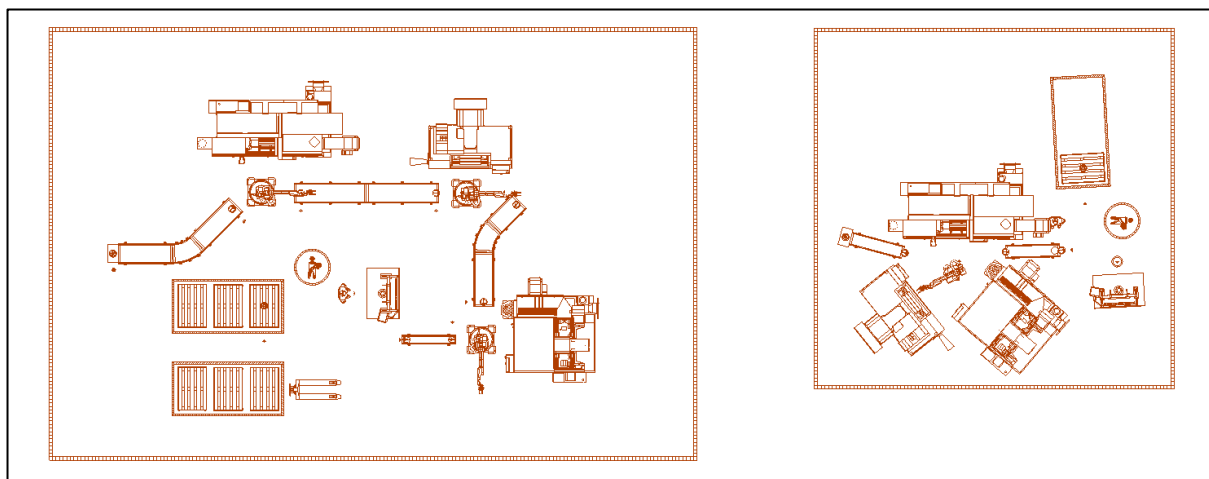


Figure 23 – Size Comparison of Original & Redesign Cell Layout

Critically, the redesigned configuration supports improved flow synchronisation and enables more effective coordination between robot motion and machine cycle times, facilitating a shift from a push-based material handling strategy towards a more integrated and flow-oriented automation system.

While the single-robot approach increases dependency on the reliability and scheduling of that resource, simulation results demonstrate that, when appropriately controlled, the benefits in reduced motion waste, improved material flow, and enhanced space utilisation outweigh the risks associated with resource consolidation.

The redesigned circular machining cell offers several additional advantages over the initial linear configuration beyond reduced motion waste and improved space utilisation. By arranging the machines in a compact circular layout, overall flow visibility and process control are enhanced, allowing operators and engineers to observe machine states, robot activity, and part movement more effectively, which supports faster detection of abnormal conditions and reduced mean time to recovery.

The reduction in transport distance and removal of intermediate conveyors also decreases non-value-adding transfer time, resulting in shorter manufacturing lead time and improved responsiveness to process variability and changing customer demand. Furthermore, the use of a single robot to tend all machines promotes improved process synchronisation, effectively pacing the system and reducing the likelihood of overproduction and excessive WIP accumulation at non-bottleneck operations. From an operational perspective, consolidating robotic assets reduces maintenance complexity, spare parts requirements, and lifecycle support costs, while also lowering energy consumption through reduced robot idle power and the elimination of multiple conveyor systems.

Figure 24 illustrates the human travel distance within the original cell configuration. The recorded values are measured in millimetres and, when converted to metres, represent a total travel distance of 91.7 m.

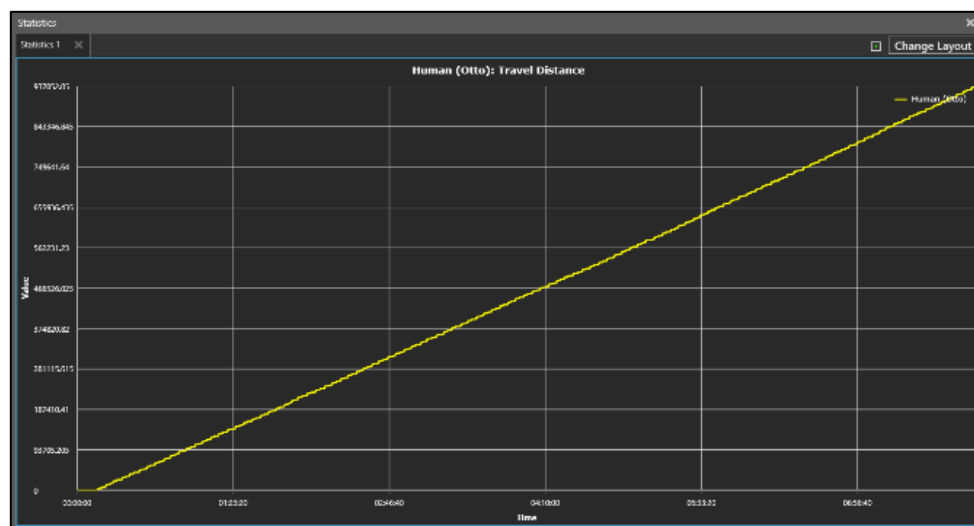


Figure 24 – Human Travel Distance in Original Cell

Whilst figure 25 presents the human travel distance within the redesigned cell layout. The recorded values are measured in millimetres and, when converted to metres, equate to a total travel distance of 44.6 m. This represents a reduction of 47.1 m when compared to the original cell configuration.

This reduction indicates that the operator is required to walk substantially less during the shift, contributing to improved operational efficiency and reduced non-value-added movement. The

difference in travel distance between the two layouts directly supports the increase in parts processed, as discussed previously.

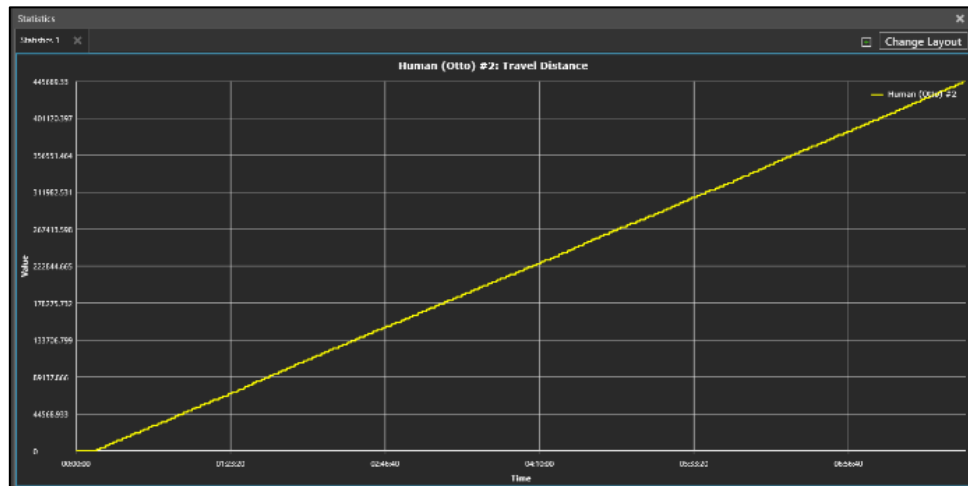


Figure 25 – Human Travel Distance in Redesigned Cell

The simplified automation architecture additionally supports greater standardisation in programming and training, improving knowledge transfer and reducing the risk of inconsistent operating practices. Finally, the compact and modular nature of the circular layout provides improved potential for integrating in-process inspection technologies and facilitates future automation upgrades, thereby strengthening long-term scalability and adaptability for high-precision piston manufacturing within a Tier-1 automotive supply environment.

4. Trade-Offs and Risk Evaluation

The redesigned circular machining cell, in which a single robot services three CNC machines, improves flow efficiency and space utilisation but introduces new system-level vulnerabilities. Consolidating all tending activity into one robotic unit creates a critical dependency, meaning any interruption to the robot would halt automated operation across the entire cell. This places greater emphasis on reliability planning, including preventative maintenance, monitoring, and structured recovery methods to preserve continuity of production.

The revised configuration also increases the demands placed on control strategy. A single robot must coordinate multiple machines with unequal cycle times, particularly where one process dominates overall capacity. Without effective sequencing and prioritisation, machine idle time may increase and reduce the expected performance benefits. The viability of the layout is therefore dependent on robust scheduling logic, bottleneck-focused servicing, and disciplined work-in-progress control.

In addition, the compact arrangement requires careful attention to safeguarding and risk management. Reduced physical separation between equipment and personnel increases the importance of defined access zones, interlocks, and standards-based risk assessment to ensure safe operation during both normal production and intervention activities.

From a capacity and investment perspective, additional milling resources would not increase throughput unless the system constraint is addressed directly. Manufacturing theory indicates that adding capacity away from the bottleneck typically increases WIP and complexity rather than output. In the short term, higher performance is more likely to be achieved through optimisation measures such as bottleneck-centred scheduling, adaptive task allocation, and variability reduction, with capital investment only justified once simulation demonstrates operation near the practical limit of the constrained resource.

Finally, full removal of manual inspection cannot be justified solely on efficiency grounds. For high-precision automotive components, inspection functions as a critical quality barrier supporting compliance, traceability, and customer assurance. Any reduction must be replaced by an equivalent or superior process assurance strategy, such as in-cycle measurement, automated gauging or vision inspection, statistical monitoring, and tool condition surveillance. A hybrid approach is typically more defensible, combining automated verification with targeted human oversight for audits and non-conformance investigation.

5. Conclusion

This project has demonstrated that the redesigned laboratory cell layout delivers measurable improvements in operational efficiency when compared to the original configuration. The revised arrangement, which positions machines closer together and consolidates machine tending under a single robotic resource, has reduced unnecessary travel distance and motion waste. As a result, throughput increased from 101 parts to 111 parts per eight-hour shift, representing a 9.9% improvement. In addition, human travel distance was significantly reduced from 91.7 m to 44.6 m, highlighting improved ergonomics and a more efficient workflow.

Despite these gains, the analysis indicates that the machining process remains constrained by the Haas VF-1, which continues to act as the primary bottleneck due to its longer cycle time. Although idle time across the cell has decreased in the redesigned layout, this has been offset by increased blocked time, suggesting that flow restrictions remain present within the system.

To improve performance further in future, Alpha Precision Components should explore strategies to reduce the impact of the VF-1 operation. This could include replacing the VF-1 with a faster or higher-capacity machine, introducing a second VF-1 to operate in parallel, or investigating process improvements that reduce machining time during the second phase. Additionally, future work could include optimising robot scheduling logic, refining buffer capacity between operations, and conducting further simulation trials to evaluate alternative configurations under varying demand conditions. Collectively, these improvements would increase throughput, reduce waiting time, and further enhance the long-term efficiency and resilience of the laboratory machining cell.

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