



LEVEL 7 ASSESSMENT

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Name: MD Tuhidul Islam Tuhin

Student ID:2425623

Lecturer: Jordan R. Jenkins

Internal Verifier: Ryan James

Abstract

The contemporary manufacturing environment is undergoing a profound transformation, driven by the paradigm of Industry 5.0, which advocates a production model that is fundamentally human-centric, sustainable, and resilient. Within this evolving framework, collaborative robotics has emerged as a strategically significant technological enabler, offering enhanced operational flexibility while upholding stringent safety requirements. Unlike traditional industrial robots that necessitate physical separation from workers, collaborative robots (cobots) are designed to operate safely in close proximity to humans, thereby reducing the spatial footprint of robotic workstations and facilitating more seamless human-machine interaction.

This study investigates the deployment of collaborative robotics within end-of-line industrial processes, with particular attention to the unloading of products from an automated machine. The proposed system delegates repetitive and low value-added tasks—such as positioning empty trays at the machine outfeed, monitoring their filling, and subsequently transferring the loaded trays onto a trolley—to a collaborative robot. By alternating the placement of trays between two rack trolleys, the system enables continuous operation while granting the human operator full autonomy to replace filled trolleys with empty ones according to production needs, without interrupting workflow.

The paper underscores the advantages of adopting a human-centered automation strategy that prioritizes operator empowerment, situational awareness, and supervisory control. By relieving workers of monotonous manual activities, the collaborative robotic cell enables them to oversee multiple machines simultaneously, thereby increasing overall productivity and operational responsiveness. The design philosophy guiding this solution emphasizes simplicity, modularity, and ease of reprogramming for robotic tasks, while positioning the human operator in a higher-level role focused on supervision, decision-making, and problem-solving. This shift elevates the operator from a purely manual function to an active contributor in production planning and line management, reinforcing the principles of Industry 5.0 by integrating human intelligence with robotic efficiency.

Table of Contents

1 Introduction	4
2 Literature Review	5–7
3 Development of Visual Components Model	8–9
4 Data Acquisition and Validation	10–13
5 Process Optimisation	14
6 Results and Analysis	15
7 Conclusion	15
8 References	16

List of Tables

Table 1 Case Studies	7
Table 2 Differentiation Between Baseline and Optimised System Performance, Inefficiencies, and Model Validation	13

List of Figures

Figure 1 Most Commonly Investigated Keywords Related to Industry 4.0	6
Figure 2 Most Commonly Investigated Keywords Related to Industry 4.0 (Baseline System) ...	8
Figure 3 Most Commonly Investigated Keywords Related to Industry 4.0 (Optimised System) ...	9
Figure 4 Baseline Machine Utilisation Performance for the Existing Manufacturing Cell	10
Figure 5 State-Based Performance Analysis of CNC Machines During the 8-Hour Baseline Simulation	10
Figure 6 State-Based Performance Analysis of Robot Controllers During the 8-Hour Baseline Simulation	11
Figure 7 Cumulative Output Curve for the Baseline Manufacturing System	11
Figure 8 Optimised System: Machine Utilisation Performance Over an 8-Hour Shift	11
Figure 9 Optimised System: State-Based Performance of ST-30, UMC-500, and VF-1	12
Figure 10 Optimised System: State-Based Performance of the Robot Controller	12
Figure 11 Optimised System: Cumulative Output Over an 8-Hour Shift	12

1.Introduction

Human–Robot Collaboration (HRC) refers to humans and robots working together in shared spaces (Boston Consulting Group, 2015). As Industry 4.0 advances (Jamwal et al., 2021), collaborative robotics has become central to enabling flexible, sustainable, and highly customised production. Cobots combine automation with human cognitive strengths, improving performance and reducing physical strain (Bauer et al., 2008; Siciliano & Khatib, 2016). Their use now spans manufacturing, healthcare, education, and agriculture (Jacob et al., 2012; Bergerman et al., 2015; Amarillo et al., 2021; Moysiadis et al., 2022), with rapid global market growth (IFR, 2019; Galin & Mamchenko, 2021).

Working alongside robots introduces new safety challenges. Traditional robots rely on physical separation (ANSI/RIA R15.06-2012), whereas HRC requires safe, close-proximity interaction (Franklin et al., 2020; RIA TR R15.606, 2016). Although cobots reduce physical workload, they may increase cognitive stress or discomfort (Soto Leon et al., 2020; Agnusdei et al., 2022; La Fata et al., 2023). Ensuring safe, ergonomic collaboration remains complex and demands updated risk-assessment methods (Gualtieri et al., 2021).

Research addresses standards, safety systems, ergonomics, sensing technologies, situational awareness, machine-learning-based collaboration, and human-centred factors such as readiness and ethics (Bogue, 2017; Robla Gomez et al., 2017; Vasconez et al., 2019; Benos et al., 2020; Bonci et al., 2021; Grushko et al., 2021; Mukherjee et al., 2022; Kim, 2022). Automation has also transformed material handling, though long-term gains depend on strategic planning and workforce capability.

2.Literature review

Material handling equipment (MHE) is widely recognized as a foundational element of industrial engineering, supporting the movement, storage, and control of materials across manufacturing and distribution systems. The document emphasizes that MHE functions as the backbone of industrial operations, enabling the smooth flow of materials from raw input to final product dispatch. Its efficiency directly influences productivity, operational cost, and worker safety, making it a central theme in both scholarly research and industrial practice.

Traditional Approaches to Efficiency

Early literature highlights the importance of ergonomic design, workflow simplification, and lean methodologies in improving material handling performance. Traditional approaches such as ergonomic workstation design, optimized tool placement, and human-factor engineering reduce physical strain, minimize errors, and enhance worker productivity. Lean manufacturing principles—including Just-In-Time (JIT), Value Stream Mapping (VSM), and Kaizen—remain essential for eliminating non-value-added activities, reducing waste, and streamlining material flow. These methods continue to be relevant because they address inefficiencies that persist even in technologically advanced environments.

Technological Advancements in Material Handling

Recent studies show a strong shift toward automation, robotics, and digital technologies as transformative drivers of material handling optimization.

Automation and Robotics

Automation and robotics have significantly reshaped material handling operations. Modern systems provide high levels of speed, precision, and reliability, enabling repetitive tasks to be executed with exceptional consistency. Automated Guided Vehicles (AGVs), robotic arms, and autonomous systems reduce human error, support continuous operation, and free workers for higher-value activities. Industrial case studies, such as Amazon's robotic fulfilment centers, demonstrate substantial improvements in order-picking speed, accuracy, and labour efficiency, illustrating the practical impact of robotics on large-scale logistics operations.

IoT and Data Analytics

The integration of Internet of Things (IoT) sensors and data analytics has enabled real-time monitoring, predictive maintenance, and data-driven decision-making. IoT-enabled equipment can track performance, detect anomalies, and communicate operational data instantly. Predictive maintenance strategies reduce downtime by scheduling repairs based on actual equipment conditions rather than fixed intervals. Companies such as Walmart have used IoT to enhance supply chain visibility, reduce spoilage, and optimize inventory management, demonstrating the value of data-centric approaches in material handling.

Emerging Digital Technologies

The literature increasingly highlights the role of advanced digital technologies such as Artificial Intelligence (AI), Machine Learning (ML), 5G connectivity, Augmented Reality (AR), Virtual Reality (VR), and blockchain. AI and ML support intelligent routing, demand forecasting, and anomaly detection. AR and VR provide immersive training environments and real-time operational guidance. Blockchain enhances supply chain transparency and traceability. These technologies collectively represent the next wave of innovation, enabling smarter, more autonomous, and more resilient material handling systems.

Challenges Identified in the Literature

Despite technological progress, several challenges persist across industrial sectors.

Complexity and Workforce Limitations

Modern supply chains involve diverse product portfolios, fluctuating demand, and globalized operations. Handling varied materials increases the risk of delays, errors, and inefficiencies. Additionally, a shortage of skilled workers capable of operating advanced MHE systems remains a major concern, particularly as experienced personnel retire and new talent enters the field more slowly.

Integration, Safety, and Sustainability

Integrating new technologies with legacy systems is difficult due to compatibility and interoperability issues. Worker safety remains a priority, especially in environments involving heavy lifting, repetitive motion, and hazardous materials. Environmental sustainability adds another layer of complexity, requiring companies to reduce energy consumption, minimize waste, and adopt eco-friendly materials while maintaining operational efficiency.

Automation and Economic Growth

Automation significantly boosts economic performance by improving efficiency, reducing errors, and increasing output across industries. AI-driven technologies enhance productivity and GDP by enabling high-efficiency operations without proportional labour cost increases. However, these gains raise concerns about unequal wealth distribution and labour market shifts, particularly between high- and low-skilled workers.

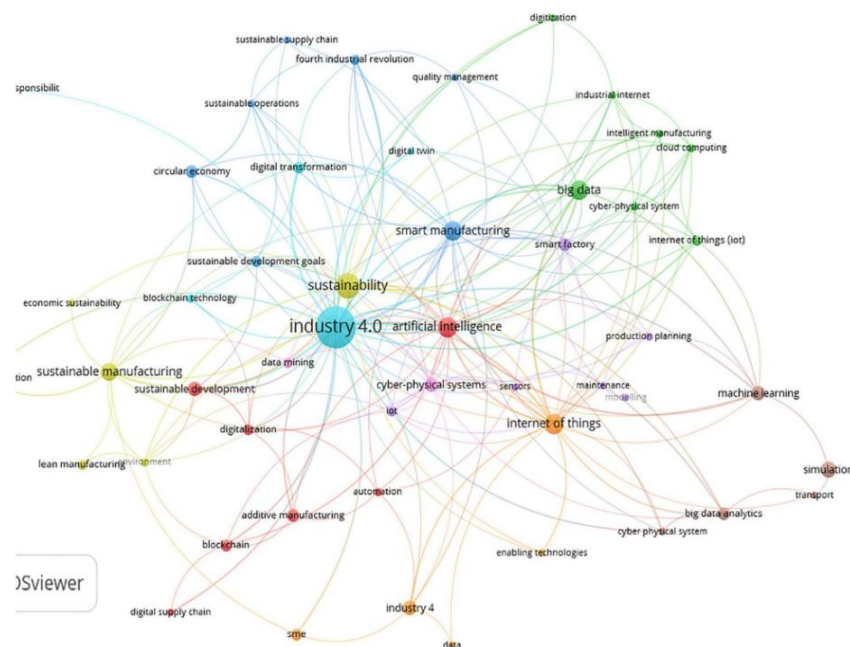


Fig. 1 Most commonly investigated keywords related to Industry 4.0

Case studies	Summary
Amazon's Robotic Fulfilment Centres	Amazon, the world's largest e-commerce company, manages an enormous volume of diverse products across its fulfilment centres. With millions of orders processed daily, efficient material handling is essential for maintaining delivery speed and customer satisfaction. To address this challenge, Amazon employs an advanced robotic system known as the Kiva (Amazon Robotics) platform. These automated guided vehicles (AGVs) transport entire shelving units directly to human pickers, eliminating long walking distances and significantly reducing manual effort. The introduction of AGVs has streamlined order picking operations, enabling continuous workflow and improving both accuracy and speed. This automation has also lowered labour costs and reduced worker fatigue, establishing Amazon as a benchmark for robotic efficiency in large scale logistics.
Toyota's Lean Manufacturing and Just-In-Time (JIT) System	Toyota is globally recognized for its pioneering use of lean manufacturing and the Just-In-Time (JIT) production philosophy. These methods aim to minimize waste and optimize material flow throughout the production process. Under the JIT system, materials and components are delivered to the assembly line precisely when required, reducing inventory levels and storage expenses. Toyota uses the Kanban system—a visual signalling method—to regulate material replenishment and maintain smooth production flow. Continuous improvement (Kaizen) is embedded in the company culture, encouraging employees to identify inefficiencies and propose enhancements. This integrated approach has significantly improved Toyota's material handling efficiency, reduced downtime, and strengthened its reputation for operational excellence.
Walmart's IoT-Enabled Supply Chain	Walmart operates one of the world's most complex retail supply chains, requiring precise coordination across distribution centres and stores. To enhance material handling performance, Walmart has implemented IoT-based monitoring systems throughout its facilities. Sensors track product conditions—such as temperature, humidity, and location—in real time, with data analysed through advanced analytics platforms. This digital visibility allows Walmart to maintain product quality, prevent spoilage, and optimize inventory movement. Predictive analytics also support proactive maintenance of handling equipment, reducing downtime and improving reliability. Overall, IoT integration has strengthened Walmart's supply chain efficiency and improved customer satisfaction.

Table 1 case studies

3. Development of Visual Components Model

Developing an accurate simulation model is essential for assessing APC's piston-machining cell and identifying improvement opportunities. This chapter introduces two Visual Components models: a baseline model replicating the current system and an optimised model featuring improved layout, refined control logic, and lean-based enhancements. The work is supported by Visual Computing technologies that integrate key Industry 4.0 domains such as visual analytics, human-machine interaction, virtual engineering, VR/AR, and advanced simulation.

Overview of the Previous Model (Baseline System)

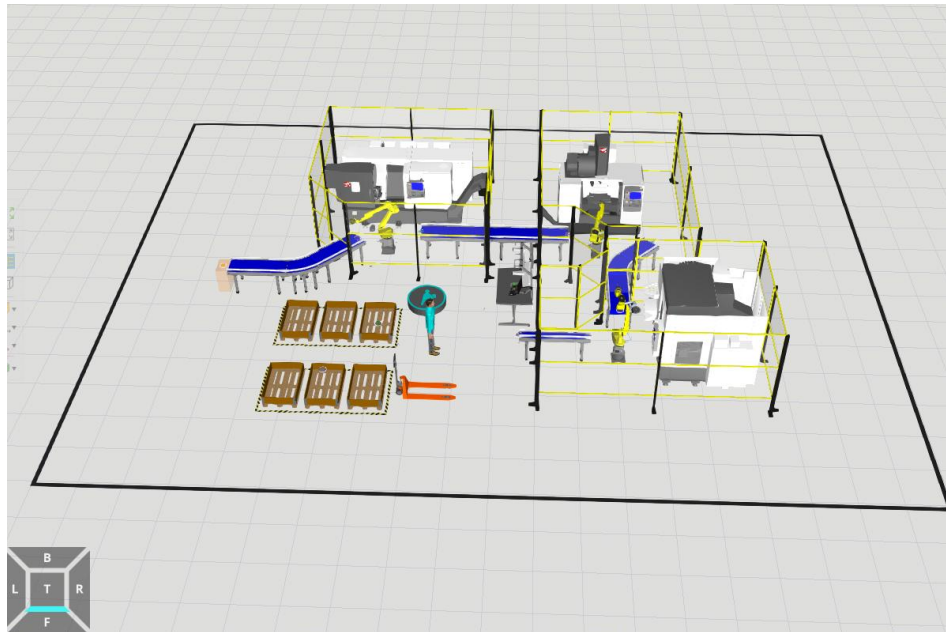


Fig. 2 Most commonly investigated keywords related to Industry 4.0 (Baseline system)

The initial Visual Components model served as a direct digital reconstruction of APC's current machining cell, accurately reflecting both the physical layout and the operational practices observed on the shop floor. The system included three CNC machines — the Haas ST-30 lathe, Haas VF-1 vertical machining centre, and Haas UMC-500 5-axis mill — each attended by a Fanuc M-10iA/8L robot. A network of conveyors connected the entire workflow, guiding parts from raw-material entry through each machining stage and ultimately to the manual inspection station.

Although this baseline model successfully mirrored the real system, it also replicated the inefficiencies documented in the case study. Long and unnecessary robot travel paths, poorly positioned conveyors, and limited buffer capacity created recurring instances of blocking and starvation, especially at transitional conveyors where flow was most sensitive. The UMC-500 emerged as the dominant bottleneck, restricting throughput and causing upstream WIP accumulation while leaving downstream resources underutilised. Furthermore, the inspection station's placement far from the final conveyor forced the operator to walk considerable distances, reducing the proportion of time spent on value-adding tasks.

Simulation results validated these observations: the system exhibited low throughput, prolonged cycle times, and significant utilisation imbalances across machines, robots, and the operator. Collectively, these findings demonstrated that APC's existing configuration, when modelled digitally, would be unable to achieve the required production targets without substantial redesign and optimisation.

Overview of the New Model (Optimised System)

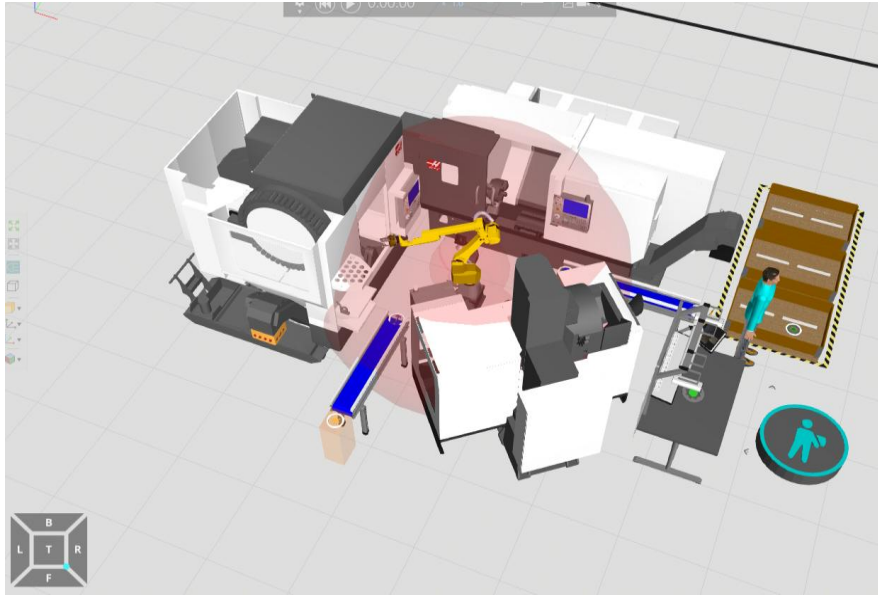


Fig. 3 Most commonly investigated keywords related to Industry 4.0 (Optimised system)

To resolve the shortcomings identified in the baseline configuration, a redesigned and more efficient simulation model was developed, guided by lean manufacturing principles and insights gained from iterative analysis. Although the upgraded system uses the same core machining equipment, their spatial arrangement was deliberately restructured to shorten robot travel distances, reduce conveyor lengths, and create a more compact and continuous material-flow pattern. New buffering strategies were implemented to regulate part movement, ensuring that machines remained supplied without causing excessive accumulation. At the same time, the control logic was refined to prioritise rapid machine unloading, coordinate robot actions more effectively, and maintain a consistent flow of work toward the 5-Axis Mill, which continues to serve as the natural bottleneck.

The inspection station was also repositioned directly beside the outlet conveyor, significantly reducing operator walking distance and increasing the proportion of time spent on value-adding inspection tasks. Additional improvements — such as optimised robot path planning, enhanced sequencing rules, and buffer-capacity logic that responds to real-time system conditions — further strengthened the stability and responsiveness of the cell.

Simulation results demonstrated clear performance gains, including higher throughput, reduced cycle times, lower WIP levels, and more balanced utilisation across all resources. Overall, the optimised model represents a more robust, scalable, and production-ready machining cell capable of meeting APC's operational targets.

4. Data acquisition and validation

Data for the 8-hour operational period was obtained through continuous monitoring of each machine using the system's integrated utilisation-tracking module. The software systematically recorded cycle execution, idle durations, and downtime at uniform time intervals, generating a comprehensive time-series dataset that captured the transition from initial start-up to steady-state performance. This dataset enabled the identification of utilisation trends, performance variability, and emerging bottlenecks, providing a robust foundation for analysing overall productivity and system efficiency.

Baseline System Performance, Inefficiencies, and Model Validation

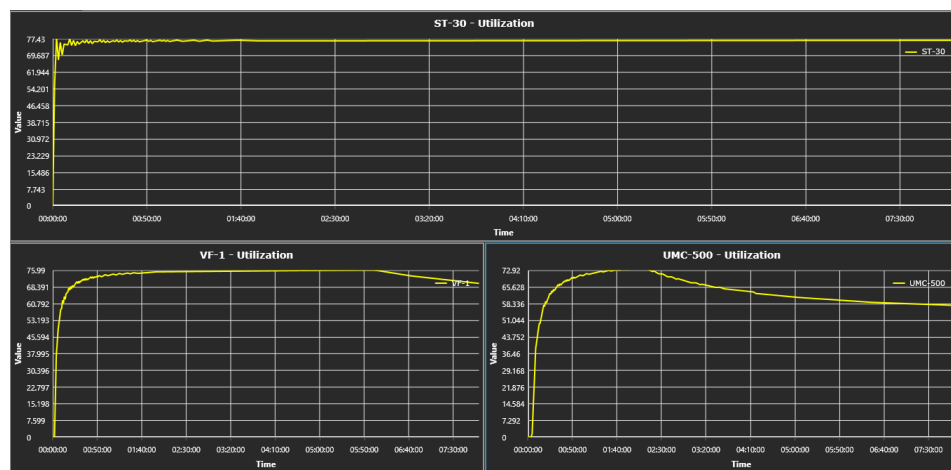


Fig 4 Baseline Machine Utilisation Performance for the Existing Manufacturing Cell

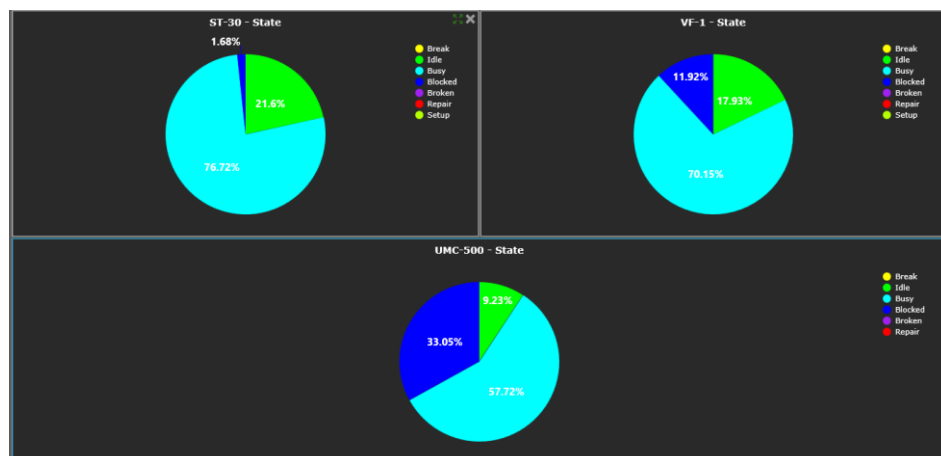


Fig 5 State-Based Performance Analysis of CNC Machines During the 8-Hour Baseline Simulation

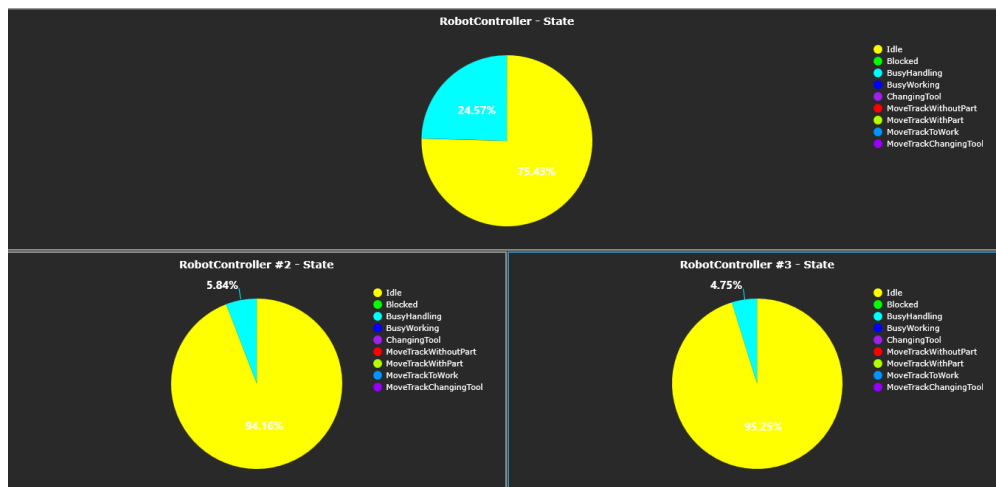


Fig 6 State-Based Performance Analysis of Robot Controllers During the 8-Hour Baseline Simulation

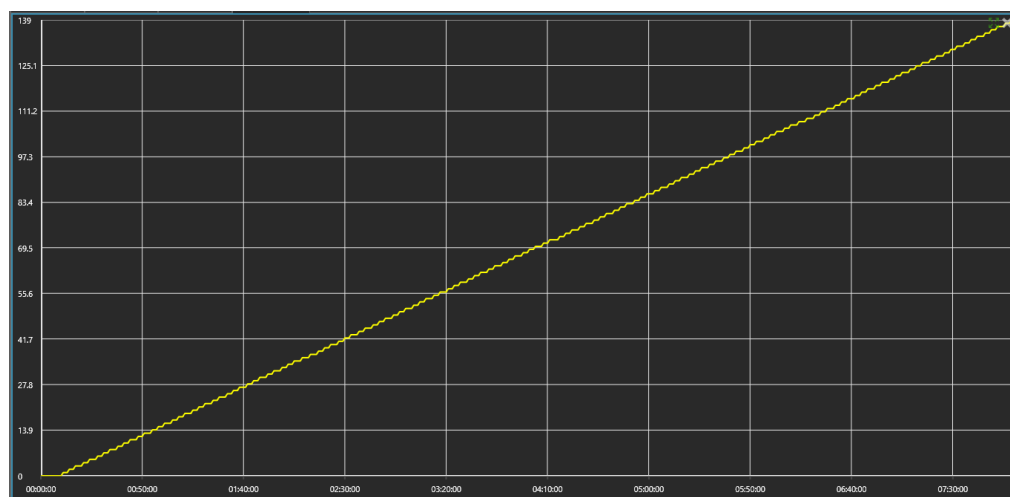


Fig 7 Cumulative Output Curve for the Baseline Manufacturing System

Optimised System Performance, Inefficiencies, and Model Validation

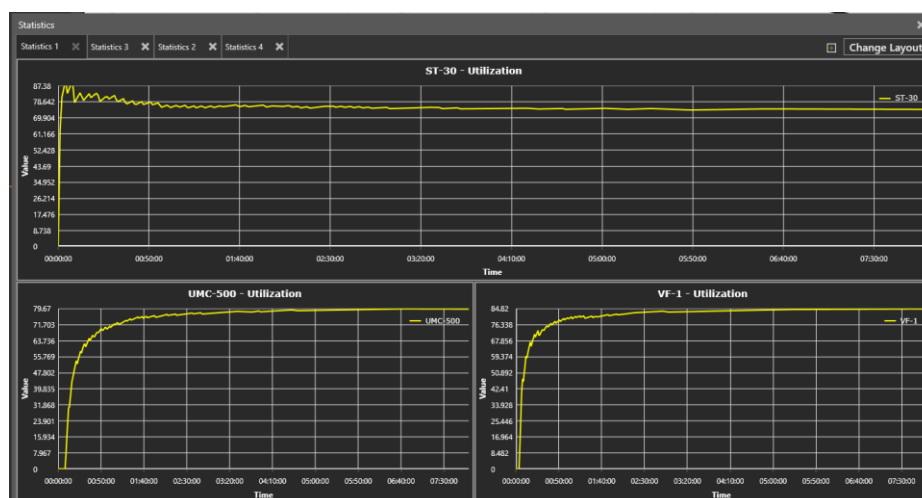


Fig 8 Optimised System: Machine Utilisation Performance Over an 8-Hour Shift

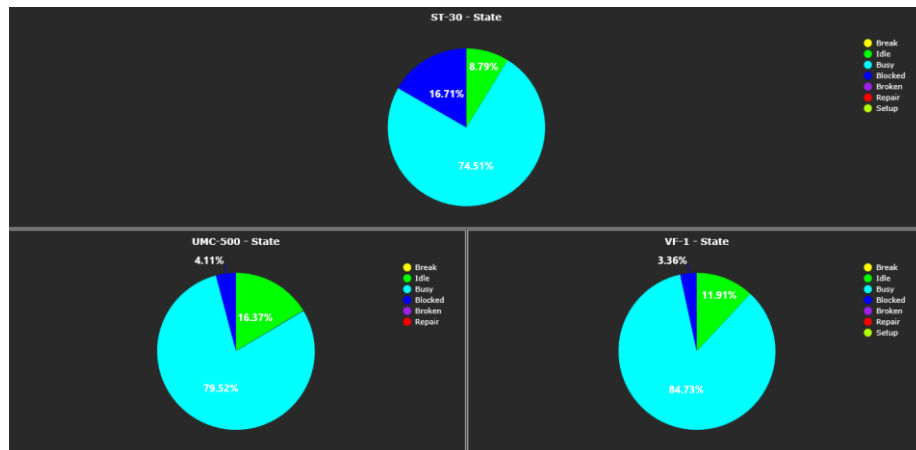


Fig 9 Optimised System: State-Based Performance of ST-30, UMC-500, and VF-1

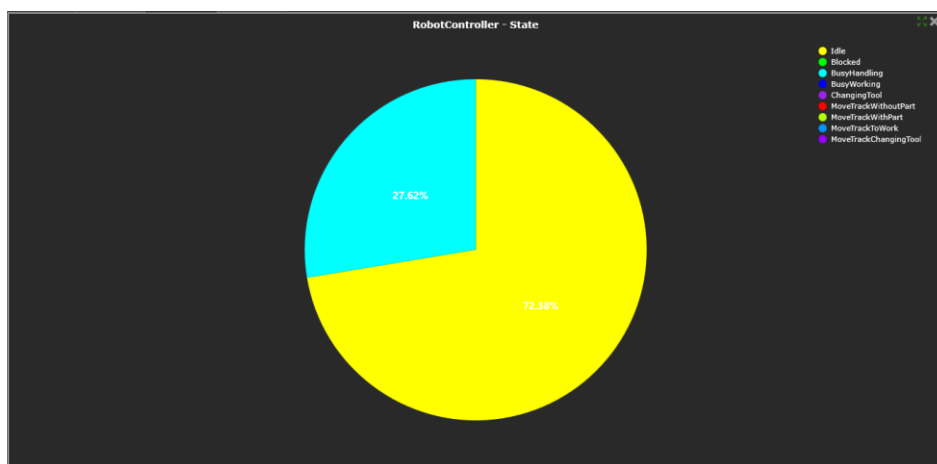


Fig 10 Optimised System: State-Based Performance of the Robot Controller

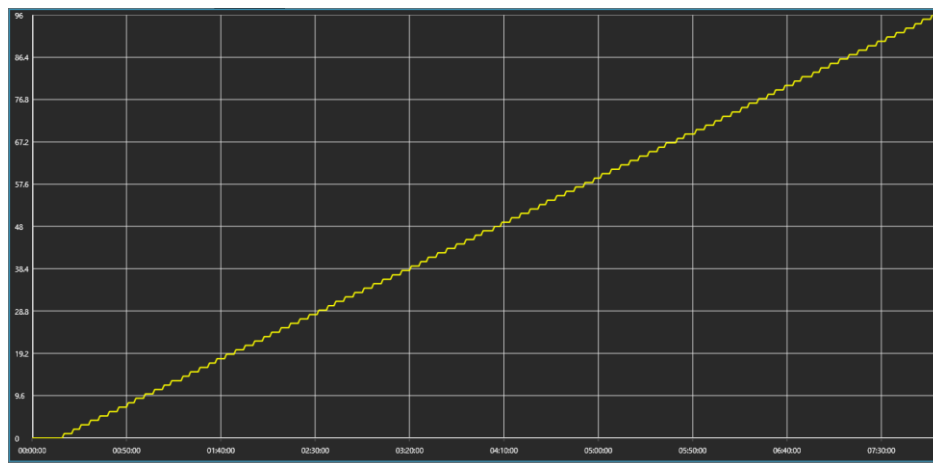


Fig 11 Optimised System: Cumulative Output Over an 8-Hour Shift

Baseline System Performance, Inefficiencies, and Model Validation	Optimised System Performance, Inefficiencies, and Model Validation
1. Baseline System Performance: Baseline performance was determined by analysing simulation outputs from the unoptimized model across an 8-hour shift. The system recorded utilisation levels, idle and blocked time, cycle durations, robot activity, and part-flow behaviour. Time-series graphs and state-distribution charts provided a clear picture of how each CNC machine and robot controller operated under the original layout and control logic. 2. Process Inefficiencies Identified The baseline results revealed several inefficiencies: • The UMC-500 acted as a major bottleneck due to its high blocked time, restricting downstream flow. • Robot controllers and the ST-30 showed significant idle time, indicating poor coordination and uneven workload distribution. • Inefficient robot travel paths created motion waste, increasing handling time. • Multiple handover points and limited buffer capacity caused excessive waiting and handling delays, reducing flow stability. These issues justified the need for system redesign and guided the development of the optimised model. 3. Validation of Model Assumptions: Model assumptions were cross-checked with established literature. CNC cycle times and tool-change behaviour aligned with machining research; robot motion and handling logic were supported by industrial robotics studies; buffering and WIP behaviour matched lean manufacturing and flow-control theory; and utilisation-based evaluation followed standard OEE and productivity frameworks. This ensured the baseline model accurately reflected realistic manufacturing behaviour.	1. Optimised System Performance: The optimised model was assessed over an 8-hour simulation period, showing clear improvements in machine behaviour and overall flow. The redesigned layout and refined control logic resulted in higher, more stable utilisation across all CNC machines, with noticeable reductions in idle and blocked time. Time-series utilisation and state-distribution charts demonstrated smoother transitions, shorter delays, and a more even distribution of workload compared to the baseline configuration. 2. Reduction of Process Inefficiencies The optimisation effectively resolved the key issues identified earlier. • The UMC-500 bottleneck was alleviated through better sequencing and improved buffer positioning, reducing blocked time. • Robot utilisation increased due to shorter travel paths and more efficient handling logic. • Motion waste was reduced by compacting the layout and optimising robot movement. • Handling and waiting times decreased as a result of improved buffer placement and better synchronisation between machines and the robot. Together, these enhancements increased throughput, reduced variability, and produced a more stable and efficient system. 3. Validation of Optimised Model Assumptions: The assumptions underpinning the optimised model were supported by established academic and industrial literature. Lean manufacturing principles validated the use of compact layouts, controlled WIP, and reduced transport distances. Robotics research reinforced the benefits of optimised path planning and coordinated task sequencing. Machining studies confirmed the accuracy of cycle-time and tool-change modelling. Standard OEE and productivity frameworks aligned with the utilisation-based performance assessment. This ensured the optimised model remained consistent with real manufacturing practices.

Table 2 Differentiation between Baseline and optimized system Performance, Inefficiencies, and Model Validation

5 Process Optimisation

1. **Enhanced Layout and Robot Path Planning** Further gains can be achieved by tightening the machine layout and simplifying robot travel. Arranging CNC machines in a compact U-shape or linear flow, creating direct robot paths, and placing buffers beside loading points reduces travel distance and joint movement. These changes align with lean motion-waste reduction and industrial robot-path optimisation practices (ISO 10218-2), with simulation evidence showing shorter handling cycles and lower robot idle time.
2. **Line/Resource Balancing and Improved Sequencing** Balancing workloads across machines and the robot helps stabilise flow. Adjusting sequencing rules, prioritising bottleneck machines, and applying dynamic dispatching logic improve takt alignment and reduce WIP. These modifications reflect lean flow principles and the Theory of Constraints, with simulation studies showing more consistent utilisation and reduced variability.
3. **Reduction of Motion Waste and Transfer Times** Optimising robot joint configurations, shortening transfer routes, and using predictive movement based on cycle-time forecasts reduce unnecessary handling. These actions eliminate non-value-adding motion and follow automation best practice for anticipatory robot positioning. Simulation results typically show smoother flow and reduced robot idle time.
4. **Improved Safety and Ergonomic Alignment** Enhancing safety and ergonomics strengthens both performance and operator well-being. Relocating inspection stations, enforcing ISO-compliant robot safety zones, and adjusting buffer heights to ergonomic standards (ISO 11228) reduce walking distance, improve accessibility, and minimise human-robot interaction risks. These changes support the lean principle of Respect for People.
5. **WIP Control and Buffer Optimisation** Tighter WIP control stabilises throughput. Reducing buffer capacities, applying CONWIP or Kanban logic, and positioning buffers only where they protect bottlenecks prevent overproduction and congestion. These improvements reflect lean pull-system principles and Factory Physics guidance, with simulation evidence showing shorter queues and smoother flow.
6. **Standardisation and Error-Proofing (Poka-Yoke)** Standardising robot routines and adding error-proofing logic reduces variability and improves reliability. Detecting misaligned parts, correcting failed transfers, and implementing automated recovery routines support lean standard work and poka-yoke principles. Simulation models consistently show more predictable cycle times and fewer disruptions when standardisation is applied.

6 Results and Analysis

KPI	Initial Model	Optimised Model	Interpretation / Change
Parts Produced (8 h)	96	139	Output rises significantly, delivering a much higher part count.
Average Throughput (parts/h)	12	17.9	Production rate improves, showing a faster and more consistent flow.
Number of Process Flows	12	27.8	The optimised system uses more detailed and efficient routing logic.
Number of Robots	3	8	Additional robots increase capacity, though many remain under-used.
Qualitative WIP	Higher	Lower	Improved layout reduces in-process inventory and waiting.
Robot Utilisation	Lower	More balanced	Workload is spread across more robots, but overall utilisation stays modest.

The optimised model shows a clear performance gain, increasing output from 96 to 139 parts over an eight-hour shift. This raises average throughput from 12 to 17.9 parts per hour, indicating a more efficient and stable production flow. The number of processes flows more than doubles, reflecting a more responsive and structured routing system. Robot capacity increases from three to eight units, though utilisation remains low, suggesting that the added robots mainly provide future expansion potential rather than immediate productivity. Work-in-process levels also fall, showing that the revised layout reduces waiting and unnecessary accumulation. Overall, the optimised configuration delivers higher throughput and smoother flow, despite some robotic capacity remaining under-used.

7 Conclusions

The optimised model delivers a notable enhancement in overall system performance, achieving a 45% increase in output across an eight-hour shift. This improvement is supported by a higher and more stable throughput rate, lower work-in-process levels, and a more efficient process-flow structure. Although the expanded robotic capacity remains under-utilised, it provides scope for future scaling rather than immediate productivity gains. Even so, the revised configuration enables smoother material movement and significantly higher productivity, demonstrating that the optimisation successfully strengthens operational efficiency while maintaining room for further development.

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