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# Robotics and Automation in Operations

**Visual Components Case Study**

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## **Abstract**

Safety, intelligence, adaptability, and system integration are the main topics of current robotics and automation research in digitally connected manufacturing environments. Beyond conventional repetitive automation, advances in machine learning, multi-modal sensing, collaborative robotics, digital twins, and cyber-physical production systems are transforming industrial operations. In order to support intelligent and adaptable production systems, this article examines these technological developments as well as new standards, control architectures, and interoperability frameworks. There is a thorough discussion of how current smart factories integrate industrial communication protocols, robotic manipulators, CNC machine tools, and human operators.

A flexible automated piston manufacturing cell with CNC machining centers, industrial robots, conveyors, and inspection procedures is the subject of an organized case study. An optimized layout design is contrasted with the initial multi-cell setup. The redesigned setup demonstrates increased operating efficiency, simplified system architecture, less robotic redundancy, and better space usage. The results demonstrate how leaner, more sustainable, and cost-effective automation systems that adhere to Industry 4.0 principles can result from strategic system redesign aided by digital simulation tools.

## Table of Contents

|                                                                        |    |
|------------------------------------------------------------------------|----|
| Overview.....                                                          | 1  |
| 1 Introduction .....                                                   | 2  |
| 1.1 Robotics Research Goals .....                                      | 3  |
| 1.2 Automation and Intelligent Control .....                           | 3  |
| 1.3 Flexible Manufacturing Systems (FMS) .....                         | 3  |
| 2 Techniques for Combining Human Operators, Robots, and Machines ..... | 3  |
| 2.1 System Architecture and Interoperability .....                     | 4  |
| 3 Strategies for Control .....                                         | 4  |
| 3.1 Human–Robot Interaction and Safety .....                           | 4  |
| 3.2 Emerging Sector Trends .....                                       | 5  |
| 3.2.1 Collaborative Robotics .....                                     | 5  |
| 3.2.2 Digital Twins .....                                              | 5  |
| 3.2.3 Industrial Digitalisation .....                                  | 6  |
| 3.2.4 Cyber-Physical Production Systems (CPPS) .....                   | 6  |
| 4 Regulatory and Standards Framework .....                             | 6  |
| 4.1 International Standards .....                                      | 6  |
| 4.2 Regional Regulations .....                                         | 7  |
| 5 A Summary of Sections 1–4 .....                                      | 7  |
| 6 Visual Components (Software) .....                                   | 8  |
| 7 Robotics and Automation for Operations .....                         | 9  |
| 7.1 Given Assignment Case Study .....                                  | 9  |
| 7.2 Optimized Assignment Case Study .....                              | 12 |
| 8 Conclusion .....                                                     | 14 |
| 9 References .....                                                     | 15 |

## Table of Figures

|                                                         |   |
|---------------------------------------------------------|---|
| Figure 1Automation and Intelligent Control process..... | 2 |
| Figure 2 FMS Process .....                              | 3 |
| Figure 3 Collaborative Robotic Arms.....                | 5 |
| Figure 4 Digital Twin Arms.....                         | 5 |
| Figure 5 Given Layout.....                              | 9 |

|                                                  |    |
|--------------------------------------------------|----|
| Figure 6 layout design in visual components..... | 10 |
| Figure 7 changed design layout.....              | 12 |

## Overview

Machines are becoming more intelligent on their own. Instead of depending only on preset patterns, modern robots can adapt by using real-time data from cameras, touch sensors, and acoustic inputs. Errors decrease and responsiveness increases because they adjust in the middle of the job. Working with people seems safer when computers can recognize motion and quickly adjust their behaviour. Instead of relying solely on preprogrammed instructions, the system makes decisions on its own initiative. Digital copies, concealed behind walls of code, reflect live equipment and identify problems before they become problems. Adjustments move more quickly across assembly lines when hardware and software are closely linked. Today's factories are more synchronized, conscious, and quick to respond.

As production environments become more interconnected, system architecture, interoperability standards, safety regulations, and cybersecurity frameworks are essential for ensuring reliable and compliant operations. International standards such as ISO 10218, IEC 61508, and IEC 62443 provide structured guidelines for the safe and secure deployment of automation, while middleware platforms and industrial communication protocols support coordination across enterprise and control levels.

In the context of current technological and regulatory developments, effective system design is crucial.

This Assignment provides a comprehensive case study of a flexible automated piston manufacturing cell that incorporates CNC machine tools, industrial robots, conveyors, and inspection processes. Starting with the initial configuration, is examined before being compared to an improved version. One can observe changes in everyday function by attentively examining how space is used and where robots are positioned. Clarity, more precise tool use, and improved product production are all benefits of a revised flow. What is notable is how modern automated lines are shaped by technological advancements combined with astute structural modifications.

## 1. Introduction

The main goals of contemporary robotics research are safety, intelligence, and adaptability. Current robotics research uses machine learning techniques and sensor technology to enable robots to operate in unexpected surroundings, in contrast to previous industrial robots that were usually programmed to do repetitive tasks in controlled environments. (Siciliano and Khatib, 2016).

Reinforcement learning and imitation learning are used in recent manipulation experiments, especially to improve grasping and skilfulness in unstructured settings. Using deep neural networks for vision-based control helps robots more accurately recognize an object's orientation, texture, and shape. Multi-modal perception, which uses vision, force torque, and tactile sensors, makes robots more reliable in assembly and inspection tasks.

Moving gently is important for machines designed to be flexible. Elastic components enable robots to manage delicate objects without causing damage. Human interaction with machinery becomes safer when flexibility is incorporated into the design. Advances in this area progress alongside the development of collaborative robots.

The concept of twin robots working is rapidly gaining traction. Instead of a single robotic leader, each robot adheres to intelligent protocols that allow them to operate collectively—routes adapt dynamically, and responsibilities shift according to availability. Warehouses employ these collaborative teams to retrieve items, load vehicles, and construct large components continuously. Teamwork is no longer exclusive to humans (Fang, Wang and Sun, 2020).

### 1.2. Automation and Intelligent Control

Data-driven optimization and model-based control are being combined more and more in automation research. Hybrid control frameworks improve strength, fault detection, and predictive maintenance capabilities by fusing AI algorithms with physics-based models. At the machine and system levels, autonomous decision-making reduces human interference while increasing operational efficiency (Schmidt *et al.*, 2020; Zhang *et al.*, 2019).

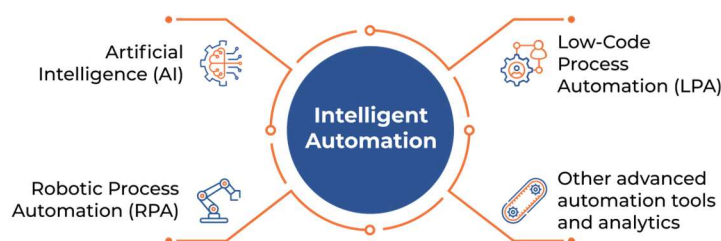


Figure 1 Automation and Intelligent Control process

Edge computing architectures are now widely investigated to support real-time data processing near production assets. This reduces latency compared to centralised cloud computing and improves system responsiveness. Furthermore, anomaly detection systems employing machine learning help identify deviations in process parameters before they lead to failures (Zhang *et al.*, 2019).

### 1.3. Flexible Manufacturing Systems (FMS)

The goal of flexible manufacturing systems is to create a wide range of goods with little expense and changeover time. FMS research focuses on reconfigurability, scalability, and modularity. Robotic cells and modular machine tools are used in reconfigurable manufacturing systems (RMS), which can be rearranged to meet the needs of the product (Koren *et al.*, 1999; Bi *et al.*, 2008).

Dynamic scheduling and resource allocation are made possible by service-oriented architectures, which expose industrial resources as networked services. Plug-and-produce capabilities, in which new machines or robots may be integrated with little reprogramming, are made possible by standardized communication protocols (Borenstein, 2010).

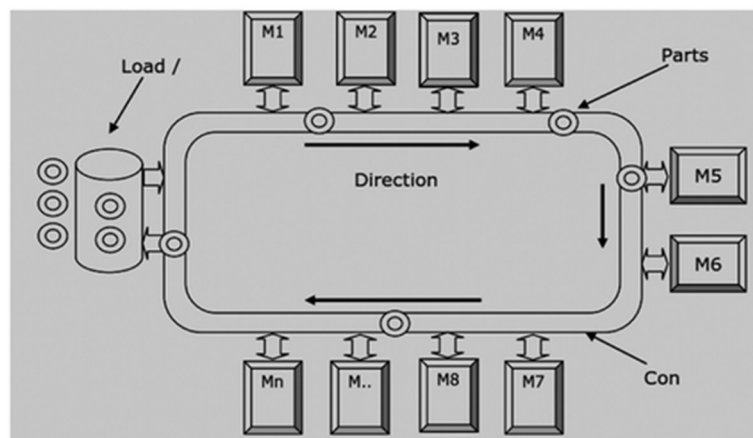


Figure 2 FMS Process

Prior to physical implementation, system layout, throughput, and scheduling are being optimized through the use of digital simulation and discrete-event modelling tools. These advancements facilitate the flexible production techniques needed in settings involving mass customization (Negri *et al.*, 2017).

## 2.0 Techniques for Combining Human Operators, Robots, and Machines

The integration of robotic systems with machine tools, material-handling equipment, and human operators requires a coherent system design, safety precautions, control hierarchies, and interoperability standards.

## **2.1. System Architecture and Interoperability**

By using standardized communication frameworks, middleware systems like Robot Operating System (ROS) and ROS-Industrial allow data sharing across different devices. At the enterprise and control levels, consistent and secure data modeling is made possible by protocols such as OPC Unified Architecture (OPC UA) and other industrial communication standards.

The International Society of Automation's (2010) ISA-95 standard, which establishes hierarchical layers ranging from corporate strategy to field devices, frequently serves as a reference for enterprise-to-control integration. Programmable logic controllers (PLCs) that are configured in accordance with IEC 61131 standards are frequently required for robot-CNC interoperability.

Real-time distributed communication is made possible by message-oriented protocols like Data Distribution Service (DDS) and MQTT. These frameworks make it easier to integrate production sites that are spread out globally.

## **3.0. Strategies for Control**

In industrial automation, hierarchical control schemes are still often used. While local controllers oversee individual robots and machines, supervisory control systems coordinate activities at the cell level. However, because of their durability and scalability, distributed and decentralized control systems are becoming more and more popular.

Robotic trajectories are optimized via adaptive control and model predictive control (MPC) algorithms while taking energy efficiency and collision avoidance into account. In cooperative settings, shared control models divide decision-making power between automated systems and human operators. Other crucial elements include safety and human-robot interaction (Lasota, Fong and Shah, 2017).

### **3.1. Human–Robot Interaction and Safety**

Advanced safety features and ergonomic design are necessary for human-robot collaboration. It is common practice to use safety-rated monitored stops, force-limited actuators, and speed and separation monitoring. Guidelines for acceptable force and pressure limitations in collaborative applications are provided by ISO/TS 15066 (ISO, 2016).

Wearable technology and augmented reality (AR) interfaces facilitate remote maintenance, training, and operator advice. Allocating tasks in accordance with cognitive and physical capabilities is ensured by human factors engineering. Risk assessments that adhere to ISO 12100 are crucial for identifying risks and putting mitigation plans into action.

## 3.2. Emerging Sector Trends

### 3.2.1. Collaborative Robotics

Cobots, or collaborative robots, are made to work safely next to people without requiring a lot of physical protection. Small and medium-sized businesses have adopted it widely thanks to manufacturers like Universal Robots. Cobots usually use compliance control and torque sensors to limit force and detect collisions (Lasota, Fong and Shah, 2017).



*Figure 3 Collaborative Robotic Arms*

Adaptive behaviour, dynamic safety zoning, and intuitive programming through demonstration are the main areas of research. Flexible production settings where human agility enhances robotic accuracy are supported by collaborative robotics.

### 3.2.2. Digital Twins

Real-time sensor data, simulation models, and predictive analytics are all integrated into digital twins, which are virtual representations of actual assets. Michael Grieves popularized the idea, which is now essential to smart manufacturing tactics.



*Figure 4 Digital Twin Arms*

Predictive maintenance, scenario analysis, and virtual commissioning are made possible by digital twins. Engineers may minimize commissioning risks, optimize cycle durations, and confirm safety compliance by modelling robotic cells prior to deployment. Continuous synchronization between digital and physical systems is ensured via integration with IoT platforms (Tao *et al.*, 2019).

### **3.2.3. Industrial Digitalisation**

The term "industrial digitalization" describes how digital technology are incorporated into various production processes. It has to do with the industry 4.0 initiative, which was unveiled at the Hannover Messe in 2011.

IoT sensors, cloud computing, big data analytics, and artificial intelligence are important technologies. While edge devices gather process data in real-time, cloud solutions provide enterprise-level analytics and benchmarking. Digital dashboards improve supply chains and industrial networks' visibility.

### **3.2.4. Cyber-Physical Production Systems (CPPS)**

Computational intelligence and physical processes are combined in CPPS. Closed-loop feedback between sensors, controllers, and actuators is a hallmark of these systems. (Lee *et al.*, 2015) claim that CPPS make self-awareness, self-prediction, and self-optimization possible.

Cybersecurity is an important factor. Requirements for protecting industrial automation and control systems are outlined in standards like IEC 62443. Strong cybersecurity measures are necessary to stop unauthorized access and system outages as connection grows.

## **4. Regulatory and Standards Framework**

International standards and local laws must be followed in the design and commissioning of automated and robotic systems.

### **4.1. International Standards**

ISO 10218-1 and ISO 10218-2 define safety requirements for industrial robots and robotic systems (ISO, 2011). These standards address risk assessment, protective measures and integration requirements.

ISO/TS 15066 supplements ISO 10218 by specifying safety requirements for collaborative operation.

IEC 61508 establishes functional safety requirements for electrical and electronic systems, defining Safety Integrity Levels (SIL).

ISO 13849-1 provides guidance on safety-related parts of control systems and Performance Levels (PL).

IEC 62061 addresses functional safety for machinery control systems.

IEC 62443 defines cybersecurity requirements for industrial automation systems.

## **4.2. Regional Regulations**

The Health and Safety at Work etc. Act 1974 in the United Kingdom lays out general obligations for companies to guarantee worker safety. Proper maintenance and safety of machinery are required by the Provision and Use of Work Equipment Regulations (PUWER).

Under Regulation 2023/1230, the outdated Machinery Directive is being replaced with stricter digital and cyber regulations that are now forming EU standards. As before, CE marking standards must be met in order to enter the market.

Every configuration, right out of the planning phase, needs to have documented risk assessments before proceeding. After those reviews are approved, validation tests are conducted. The method satisfies the necessary standards only once both processes produce definite results.

## **5. Summary on 1-4**

Here, robots perform repetitive duties and machines communicate with software; this combination is transforming the way industries run. Recent research suggests intelligent adjustments based on real-time data, easily interchangeable parts, and flexible configurations. Nevertheless, assembling everything quickly becomes a tangle; systems need to adhere to shared languages and explicit designs in order to function simultaneously. Devices across the line can only truly understand one another at that point.

Even when robot tasks carry danger, results often grow. Still, working side by side means staying alert at all times - on top of thorough safety checks.

When machines copy themselves inside smart factories, problems could be spotted early - yet hidden digital risks grow at the same time. Finding a consistent balance between keeping strong under duress and staying linked up matters most. Extra internet hooks encourage difficulties, notwithstanding the benefits of automation intelligence. Without posing a danger, a steady middle ground keeps things going. Limits inside connections are necessary for smooth operations. When connected, even intelligent systems require guardrails. Strength is demonstrated not only by speed but also by how well it endures testing.

However, as machines make decisions for themselves, regulations must change. Overlap between national legislation facilitates cross-border factory operations. What is true now might not be in the future.

## 6. Visual components (software)

Visual Components is a popular offline robot programming and 3D manufacturing simulation program used in factory planning and industrial engineering. Prior to actual deployment, it allows users to design, model, and optimize production systems in a virtual setting. In contemporary manufacturing, software is crucial, especially for the creation of digital twins and smart factories.

Visual Components is how it builds realistic 3D layouts of factories. Not only can engineers design machines, robots, and conveyor systems, but they also test how materials flow through them. Because issues show up early, teams fix delays, speed up cycles, while boosting daily performance. According to the Visual Components 2024 report, testing digitally means less setup trouble and fewer costly fixes once built.

A key feature stands out - offline robot programming. Thanks to support for major brands such as ABB or KUKA, testing robot tasks in a virtual setting becomes far more practical. With this setup, coding happens separate from live operations, so factory work keeps moving. Downtime drops significantly since adjustments occur off the main line. Furthermore, complicated automation systems become more customizable and flexible when Python scripting and PLC communication are combined.

A forward-thinking factory. Teams run live copies of machines directly on their screens rather than waiting for malfunctions. Before anything occurs, these mirrors of actual equipment display every motion. Errors disappear more quickly because configurations can be tested without coming into contact with metal. The model alerts the user hours before a component stops down. Cross-border pressure rises in varied ways, but some tools remain constant. Among these, software influences the speed at which changes are implemented. Imagine making changes while you watch the results appear in a matter of minutes. Efficiency increases by seeing more clearly rather than by exerting more effort. Eliminating guesswork lowers costs.

Visual Components software is a crucial instrument in contemporary automation and manufacturing engineering. It is useful for engineers and businesses looking for production systems that are accurate, efficient, and innovative because of its skills in 3D simulation, robot programming, and process optimization.

## 7. Robotics and Automation for Operations

### 7.1. Given Assignment Case Study

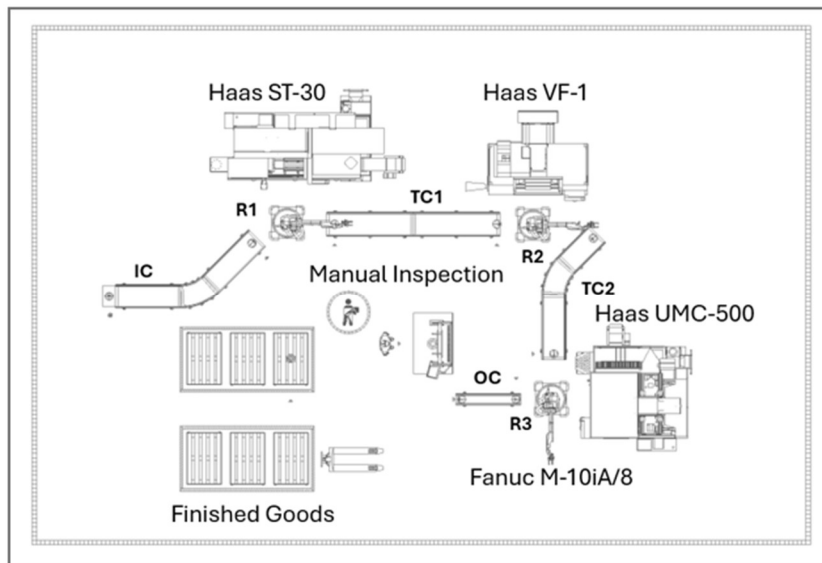


Figure 5 Given Layout

Precision pistons are made using a structured, multi-stage machining process in a flexible automated manufacturing cell as shown in figure 5. The system improves productivity, repeatability, and quality control by combining cutting-edge CNC machine tools, industrial robotics, and material handling equipment. A Haas UMC-500 5-Axis machining center, a Haas VF-1 Vertical Machining Center (VMC), and a Haas ST-30 CNC lathe are examples of essential equipment. Fanuc M-10iA/8L industrial robots, conveyors, pallet storage, and a manual inspection station are used for automated handling in between processes. The concepts of modern automated production systems are demonstrated by the methodical movement of each component through turning, milling, finishing, and inspection.

A raw piston blank is machined as part of Operation 1 (Op1), the initial stage of manufacture. First, Robot R1 loads a raw component into the Haas ST-30 CNC lathe after removing it from the inlet conveyor (IC). The ST-30 is capable of both internal and external machining tasks and is built for high-performance turning applications. The lathe performs crucial roughing and semi-finishing tasks such as face, external diameter turning, boring, and profiling at this phase. These processes establish the piston's fundamental geometry, guaranteeing correct concentricity and dimensional stability. Automated loading reduces operator reliance and idle time, while CNC control offers great precision and reproducibility. Robot R1 unloads the part after it has been machined and moves it to Transitional Conveyor 1 (TC1) for the subsequent process.

Robot R2 takes the partially completed item from TC1 and inserts it into the Haas VF-1 Vertical Machining Center. Inside Op2, that equipment is used for both drilling and milling. The next stage following retrieval is loading. The VF-1 is intended for operations involving precise drilling, tapping, and milling. Features including oil galleries, machined flats, and piston pin

bores are made at this point. Maintaining geometric tolerances between milled and turned parts requires precise fixturing and placement. CNC programming ensures that tool paths remain accurate and that surfaces are consistently produced. Without slowing down, automated tool exchanges aid in reducing cycle times. Robot R2 picks up the part after cutting ends and transfers it to Transitional Conveyor 2 (TC2). A smooth production flow is encouraged, and work-in-progress accumulation is decreased by this well-organized transfer between processes.

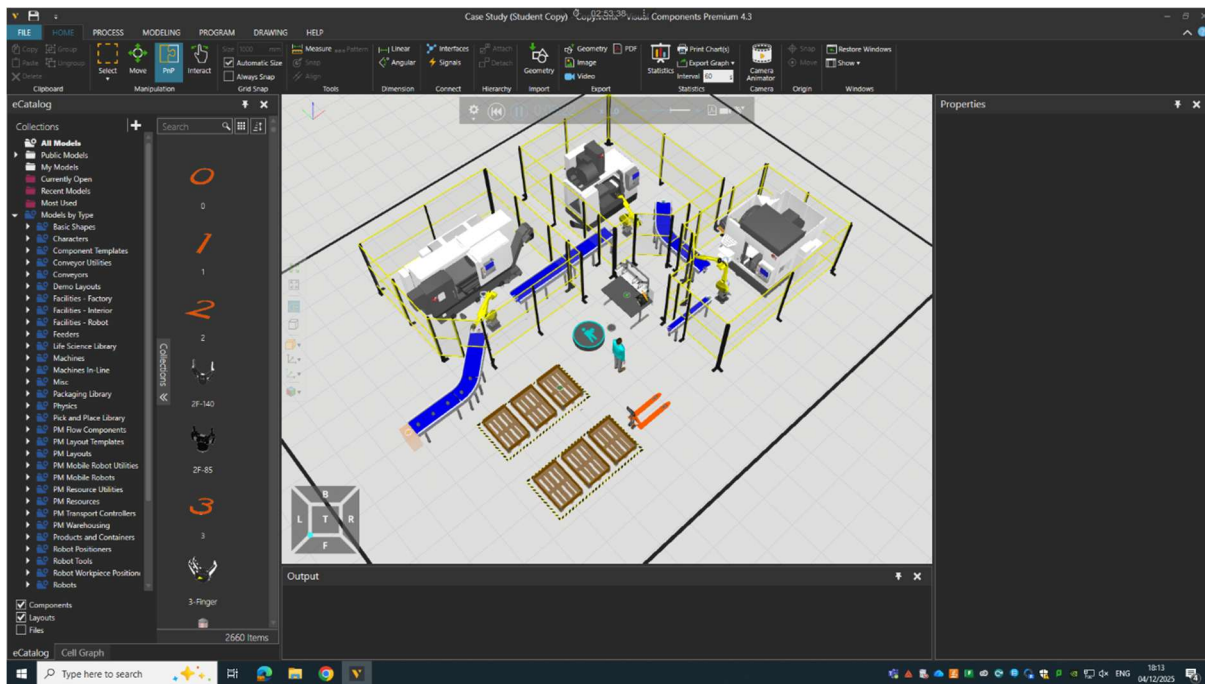


Figure 6 layout design in visual components.

Robot R3 inserts the part into the Haas UMC-500 for Op3 after removing it from TC2. This 5-axis machining center's ability to move across several axes simultaneously allows it to tackle complicated forms with ease. Due to the fact that movements occur in unison, fewer fixturing adjustments are required. Precision is necessary for shaping piston crowns and skirts, and the UMC-500 provides it without the need for additional procedures. With each cut, accuracy remains high, maintaining a constant surface quality. Five-axis machining increases dimensional uniformity and reduces repositioning mistakes. The component's overall performance and durability are improved by the finishing process, which guarantees that crucial characteristics meet stringent technical tolerances. Robot R3 loads the completed piston onto the outlet conveyor (OC) after unloading it.

Manual inspection is the last step in the routing process. Parts are collected by a human operator from the conveyor system's terminus and moved to a specific inspection workstation. Precision tools like surface finish testers, bore gauges, and micrometers are used at this station to measure dimensions. Another kind of quality control is manual inspection, which verifies that machining procedures have followed tolerance specifications. Approved pieces are added

to the pallet of finished goods for storage or shipping following inspection. A hybrid manufacturing strategy that strikes a balance between responsibility and efficiency is demonstrated by this combination of automated production and human quality monitoring.

From the standpoint of manufacturing systems, this cell exemplifies a number of crucial contemporary production engineering concepts. First of all, automation boosts output by reducing idle time spent on manual loading and unloading. Because Fanuc M-10iA/8L robots eliminate direct operator-moving machinery contact, they improve worker safety and enable constant cycle timing. Second, the process specialization made possible by the staged routing structure maximizes machining efficiency and quality by optimizing each machine tool for a particular purpose, such as turning, milling, or multi-axis finishing. Thirdly, transitional conveyors help eliminate bottlenecks between activities and encourage continuous flow.

Scalability and flexibility are made possible by the configuration. With CNC programming, design changes can be made digitally without requiring major mechanical changes. Updated tool paths can be uploaded to the appropriate machines in the event that the piston geometry changes. Robotic programs can also be adjusted to accommodate different part sizes. which prioritize digital control, automation, and networked systems to improve market responsiveness.

## 7.2. Optimized Assignment Case Study

### 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

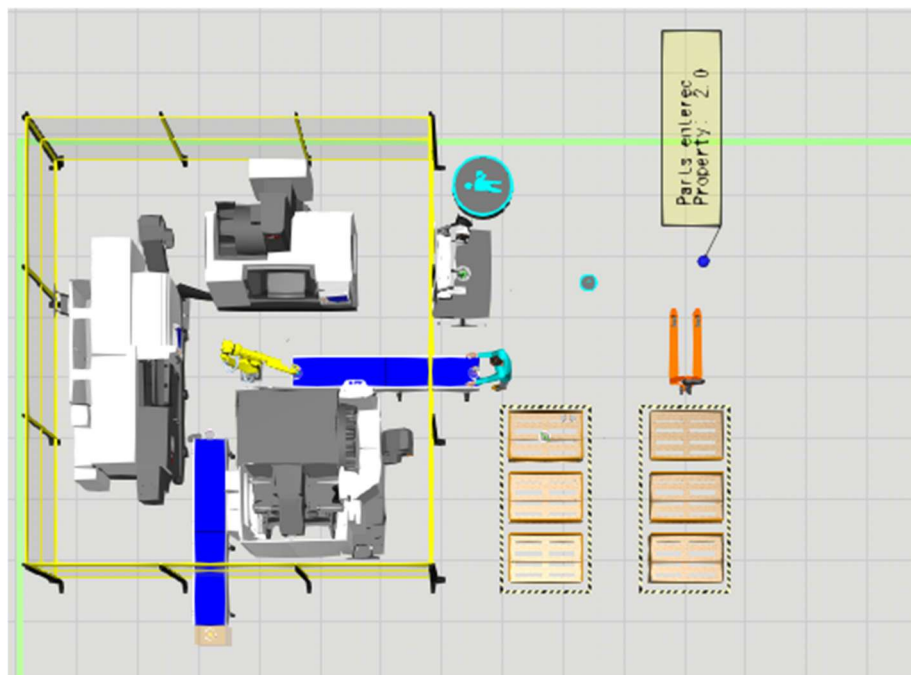


Figure 7 changed design layout.

Compared to the provided layout design and system-wide organization, the optimized layout design provides a more condensed and resource-efficient configuration as show in figure 7. The optimized architecture combines operations into a single, integrated cell, as opposed to the provided structure, which displays three distinct production cells connected by numerous conveyor segments and serviced by over three robotic manipulators. Space usage, equipment consolidation, and operational efficiency are all significantly impacted by this arrangement

Three enclosed enclosures are used for production in given layout arrangement. Conveyors connect the cells for material transmission, and each enclosure has specialized robotic units and large processing equipment. The system's physical footprint grows as a result of this architecture, which also permits modular extension and a distinct division of functions. More floor space is required for intercell transit channels, several robot work areas, and safety clearances because to the scattered structure. The overall space density is further decreased by the requirement for separate safety barriers, access zones, and maintenance clearance for every robotic unit.

A four-dimensional merging technique is reflected in the updated layout. The primary machine, a vertical conveyor interface, and one robotic manipulator are all housed in a single enclosed cell that serves as the operational hub. By placing the conveyor vertically inside the cell rather than across several enclosures, the material handling infrastructure's linear spread is lessened. Internal transit distances are reduced by this vertical layout, which improves the closeness between processing and handling operations. As a result, the arrangement maintains functional connectedness while making better use of the available floor space.

The reduced number of robots is a significant modification to the optimum configuration. The streamlined arrangement consolidates tasks into a single robotic unit, whereas the old configuration used many robotic arms to control various stations. There are various advantages to this modification. In the first place, it lowers the initial investment required for safety systems, controllers, and robotic hardware. Second, it reduces the need for maintenance and energy use. Third, it eliminates the need for inter-robot synchronization, which simplifies programming and coordination. Fewer robotic interfaces reduce complexity and possible failure sites, which can improve reliability from the perspective of systems engineering.

Equipment is arranged closer together inside the safety enclosure to maximize space use. This small arrangement saves unnecessary fencing and idle area between machines. Although they are situated nearer to the processing cell, external pallet staging areas are still reachable, allowing for more effective material input and output processes.

Compared to the given layout, the optimized layout makes every square foot longer and organizes equipment more neatly. Clearer connections result from using less space overall—fewer machines managing more tasks within a single station. By reducing the number of robotic units and combining jobs, this change lowers costs without requiring additional processes. The structure, which is based on tight integration, relies on accomplishing more with less in order to reduce clutter and free up floor space. Efficiency increases as footprint decreases, demonstrating how longer-term operation is supported by simpler flow.

## **Conclusion**

The impact of system redesign on manufacturing performance is demonstrated by the comparison of the initial and improved case study layouts. Conveyors, robotics, and CNC machines were all successfully incorporated into an automated cell in the original design. This design is improved by the optimized layout, which streamlines operating flow, reduces robotic redundancy, and enhances spatial organization. The updated layout reduces system complexity and improves space efficiency by combining operations into a single integrated cell and eliminating pointless material handling pathways. There will be less need to fix items and coordination across activities will be easier with fewer robots. Because of the reduction in upfront costs and continuous maintenance, operations function more smoothly. High quality and consistent production are maintained, while systems are given more flexibility to adjust without undue stress. In line with modern production logic, intelligent equipment placement shows more efficient uses of time, space, and materials. When design decisions prioritize lifespan and reduced costs over complexity, efficiency develops subtly.

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