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Towards Digital Twins: Exploring Offline Simulation for Production

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Introduction

In recent years, the industrial landscape has undergone significant transformation driven by advancements in technology. The advent of Industry 4.0 has brought forth a paradigm shift, emphasizing the integration of digital technologies with physical systems to create smarter, more efficient manufacturing processes. Prior to the emergence of Digital Twins (DTs), industries relied heavily on traditional simulation and modeling techniques that, while useful, often lacked the capability to provide real-time insights and adaptive responses to dynamic changes in the environment.

Historically, manufacturing and production systems have faced challenges in achieving real-time visibility and control over operations. Conventional methods such as static simulations and periodic data collection were insufficient in addressing the complexities of modern industrial processes. Operators and decision-makers struggled with delays in data acquisition and analysis, which hindered their ability to respond promptly to emerging issues and optimize performance.

The introduction of Digital Twin technology has revolutionized the way industries approach these challenges. A Digital Twin is a virtual replica of a physical system that is continuously updated with real-time data, enabling seamless monitoring, analysis, and optimization. This integration of real-time data allows for enhanced decision-making, predictive maintenance, and the ability to test various scenarios without impacting actual operations.

This work aims to explore the concept of Digital Twins and their application within a learning factory environment. Although the physical implementation of the learning factory was delayed, we have taken significant steps towards this goal by developing offline simulations using FlexSim. These simulations serve as a precursor to the eventual deployment of a full-scale Digital Twin, providing valuable insights into the potential benefits and challenges associated with this technology.

The following sections will delve into the theoretical foundations of Digital Twins, the methodology adopted for simulation development, and the results obtained from our simulations. Furthermore, we will discuss future research perspectives, emphasizing the critical role of human factors in advancing towards Industry 5.0, where the synergy between humans and intelligent systems paves the way for more sustainable and efficient industrial operations.

Chapter I

Exploring Key Aspects of the Digital Twins Domain

In this section, we delve into various facets of this domain, offering insights into its many advantages and critical aspects. We explore the breadth of topics related to this field, highlighting key advantages and crucial insights that shape our understanding and application of these principles.

I.1 Digital twins

A digital twin (DT) is a virtual replica that precisely mirrors a physical entity as we see in I.1, encompassing its components, assets, systems, and processes. This digital counterpart maintains a dynamic and continuous synchronization with its physical counterpart through the continuous exchange of data from various sensors, IoT (Internet of Things) devices, and other data acquisition technologies. The virtual model not only reflects the current state of the physical entity but also enables advanced simulation, analysis, and optimization, providing a comprehensive understanding of its lifecycle and performance.[15]

The digital twin concept integrates various advanced technologies, including IoT, artificial intelligence (AI), machine learning (ML), big data analytics, and cloud computing, to create a robust and detailed virtual representation. This virtual representation evolves over time, capturing the comprehensive history, current state, and future states of the physical entity. Unlike static 3D models or simulations, digital twins offer dynamic and interactive capabilities that provide valuable insights, predictive capabilities, and data-driven decision-making support.[9]

The implementation of digital twins can have a significant impact across various industries, from manufacturing and infrastructure to healthcare and urban planning. In the manufacturing sector, digital twins can be used to simulate production processes, optimize equipment maintenance, and predict potential failures, leading to improved efficiency, reduced downtime, and increased productivity. In the infrastructure domain, digital twins can be applied to monitor the condition of bridges, buildings, or transportation systems, enabling proactive maintenance and enhancing public safety. In the healthcare industry, digital twins of patients or medical devices can facilitate personalized treatment plans, remote monitoring, and improved medical outcomes.[16]

The continuous evolution and refinement of digital twin technologies, coupled with the growing availability of IoT devices and the increasing computational power of cloud-based platforms, have made this concept more accessible and practical for a wide range of applications. As the digital twin ecosystem matures, organizations across various sectors are recognizing the transformative potential of this technology to drive innovation, enhance decision-making, and optimize the performance of their physical assets and systems.[4]

I.1.1 Types of DT

I.1.1.1 Component Twins

Digital twins are virtual replicas of physical components or elements within a system. These digital counterparts closely monitor the performance and state of crucial components, enabling predictive maintenance and timely corrective actions. For example, a digital twin can closely observe the wear and tear of a machine part, forecasting when it will require replacement [4].

I.1.1.2 Asset Twins

Asset duplicates reflect the entirety of physical items, like machinery or transportation. By merging data from many parts, asset duplicates deliver a complete picture of the asset's functioning. This overall perspective allows for operational enhancements and forecasted upkeep, ensuring the asset runs smoothly and dependably throughout its lifetime.[17]

I.1.1.3 System Twins

System replicas mirror full-scale systems, like manufacturing processes or electrical networks. These replicas enable the simulation and examination of how different parts of a system impact one another. By exploring these relationships, businesses can enhance the efficiency and dependability of their integrated operations and parts, thereby optimizing overall performance.[17]

I.1.1.4 Process Twins

A digital mirror that mirrors an entire operation, like a factory or a distribution network, is called a process twin. These virtual duplicates help refine the productivity of these procedures by spotting where problems and inefficiencies occur. For instance, a digital replica of a supply chain can experiment with different approaches to find the most efficient routing and inventory management techniques.[18]

I.1.1.5 Environmental Twins

The digital counterparts of real-world environments, like smart cities or large buildings as shown in the figure I.2, are known as environmental twins. These virtual replicas combine data from diverse systems and resources to enhance the management and performance of intricate settings. For instance, an environmental twin in a smart city can help regulate traffic patterns, energy consumption, and public utilities.[19]

I.1.2 Advantages of Digital Twins

Digital twins offer numerous benefits across various domains, including:

I.1.2.1 Improved Operational Efficiency

Digital replicas provide real-time tracking and management of physical items and workflows. This allows for enhanced performance, less disruption, and more streamlined operations. Businesses can leverage these digital replicas to constantly monitor and fine-tune their processes for maximum efficiency.[20]

I.1.2.2 Predictive Maintenance

Digital twins provide companies unprecedented insights into the health and performance of critical assets and infrastructure. By creating virtual replicas that mirror physical systems, digital twins enable organizations to forecast potential failures with remarkable accuracy. This predictive maintenance approach allows companies to extend asset lifespan, optimize operational efficiency, and minimize costly disruptions. Digital twins bridge the gap between the digital and physical realms, transforming asset management and equipment maintenance to unlock new levels of predictability, resilience, and competitive advantage.[21]

I.1.2.3 Enhanced Decision Making

Digital replicas offer comprehensive insights and analytics, empowering data-driven choices. They enable the exploration of various scenarios, revealing potential consequences and effects. This functionality assists managers in making well-informed decisions, relying on precise, up-to-the-minute data.[20]

I.1.2.4 Cost Savings

Streamlining processes, minimizing maintenance expenses, and avoiding unexpected disruptions can generate substantial cost savings. Digital replicas empower businesses to pinpoint inefficiencies and opportunities for enhancement, ultimately leading to reduced operating costs and enhanced profitability.[21]

I.1.2.5 Product Development and Innovation

Digital twins allow testing and checking of new designs and processes in a virtual setting. This speeds up the product development process and encourages innovation. Engineers can use digital twins to experiment with and test new products in a virtual world before building actual prototypes.[22]

I.1.3 Reasons Companies Need Digital Twins

I.1.3.1 Efficiency and Productivity

Businesses strive to enhance their operations and boost productivity. Digital duplicates provide real-time information and management, resulting in more efficient processes and increased output. For instance, a manufacturing facility can leverage digital duplicates to streamline production and minimize waste.[23]

I.1.3.2 Risk Management

Digital replicas empower organizations to foresee and address risks through advanced data analysis and scenario testing. This helps minimize the chances of malfunctions and incidents. For sectors like aviation and medicine, these digital counterparts can bolster safety by anticipating and averting possible problems.[24]

I.1.3.3 Sustainability

Harnessing the power of digital twins, companies can enhance their environmental sustainability. These virtual replicas enable precise tracking and control of energy usage, emissions, and resource management, thereby minimizing waste and optimizing operations. Through this data-driven approach, businesses can significantly reduce their ecological footprint and contribute to a more sustainable future.[25]

I.1.3.4 Customer Satisfaction

Embracing digital twins empowers companies to enhance their product's quality and durability, ultimately fostering greater customer contentment and loyalty. When products consistently meet lofty standards of excellence and functionality, businesses can forge more robust connections with their clientele.[26]

I.1.4 Fields of Application

I.1.4.1 Manufacturing

Digital twins are used to optimize production lines, monitor equipment health, and improve product quality. They enable manufacturers to simulate production processes, identify inefficiencies, and implement improvements.

I.1.4.2 Healthcare

Digital twins of medical devices and patient-specific models enhance treatment planning, predictive maintenance of equipment, and personalized healthcare. For example, a digital twin of a medical device can predict maintenance needs and ensure it operates correctly.

I.1.4.3 Aerospace

In the aerospace industry, digital twins help in the design, testing, and maintenance of aircraft, improving safety and efficiency. Engineers can use digital twins to simulate flight conditions and optimize aircraft performance.

I.1.4.4 Energy

Energy companies use digital twins to optimize the performance of power plants, grids, and renewable energy installations. Digital twins can monitor energy production, predict maintenance needs, and optimize energy distribution.

I.1.4.5 Automotive

Digital twins in the automotive industry support the design, manufacturing, and maintenance of vehicles. They help improve vehicle performance, reduce costs, and accelerate development cycles.

I.1.4.6 Smart Cities

Digital twins of urban environments help manage infrastructure, optimize resource usage, and improve the quality of life for residents. Cities can use digital twins to monitor traffic, manage public services, and plan urban development.

I.1.4.7 Construction

In construction, digital twins are used to plan, monitor, and manage building projects. They ensure projects are completed on time and within budget by providing detailed insights into project progress and potential issues.

I.1.4.8 Logistics and Supply Chain

Digital twins help in optimizing supply chain operations, improving inventory management, and enhancing logistics efficiency. Companies can use digital twins to simulate supply chain scenarios and find the most efficient strategies.[27]

I.2 Digital model

A **Digital model** A digital model is a virtual duplicate of a real-world item, system, or operation. It's made using advanced digital tools and technologies, such as computer-aided design (CAD) software, simulation programs, and complex mathematical models. The digital version accurately mimics the intricate features, dynamic actions, and interconnected components of its physical counterpart, allowing people to thoroughly analyze, visualize, test, and optimize the design in a virtual setting before creating the actual thing.[6]

These digital models have become an indispensable tool in a wide range of industries, including engineering, manufacturing, architecture, and healthcare. In the field of engineering, for example, digital models enable engineers to experiment with different design concepts,

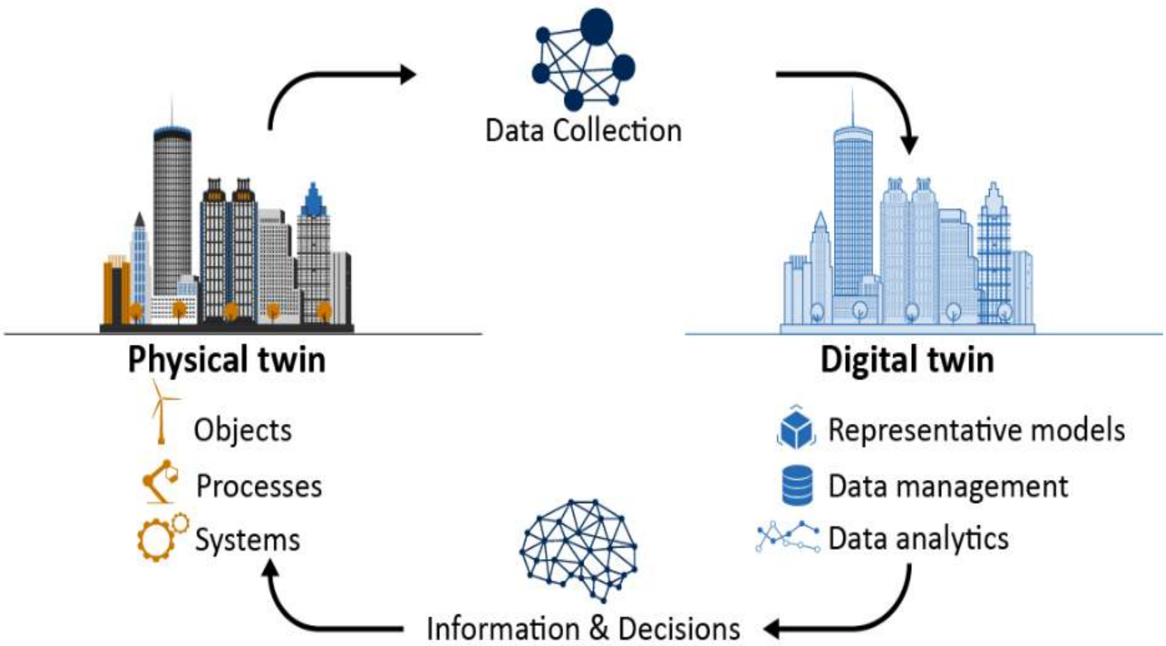

Figure I.1: Connection between physical twin and virtual twin

identify potential issues, and refine the product without the need for costly physical prototypes. Architects can use digital models to create virtual walkthroughs of their proposed buildings, allowing clients and stakeholders to experience the space and provide valuable feedback before construction begins.[6]

In the healthcare sector, digital models have revolutionized the way medical professionals approach diagnosis, treatment planning, and even medical device development. Surgeons can now practice complex procedures using virtual replicas of a patient's anatomy, enhancing their skills and reducing the risks associated with real-world operations. Pharmaceutical companies can use digital models to simulate the behavior of new drug compounds, accelerating the drug discovery and development process.[6]

The profound impact of digital models extends beyond just these specific industries. By boosting design efficiency, lowering development costs, and enhancing overall performance, these virtual representations of real-world systems have become an integral part of the modern world, driving innovation, improving decision-making, and transforming the way we approach problem-solving across a multitude of sectors.[6].

I.3 Digital Shadow

Digital Shadow

A **digital shadow** Digital replicas, also known as digital shadows, provide a virtual representation that preserves comprehensive historical and real-time information about a physical entity, system, or activity. Unlike digital twins, which dynamically simulate the behavior and conditions of their physical counterparts in real-time, digital shadows focus on storing and examining past and present data to offer valuable insights, identify trends, and enable predictive analytics.

Figure I.2: The Physical system and the virtual system

The primary advantage of digital shadows lies in their role as data repositories, allowing for retrospective analysis and optimization based on the accumulated knowledge and trends over time. By maintaining a comprehensive record of a physical system's performance, digital shadows empower organizations to make informed decisions, track and monitor key performance indicators, and implement proactive maintenance strategies.

In contrast to digital twins, which are designed to mirror the real-time dynamics of their physical counterparts, digital shadows concentrate on providing a deeper understanding of the historical context and long-term patterns that shape the behavior and evolution of a physical system. This distinction enables digital shadows to serve as a crucial complement to digital twins, offering a more holistic view of the system's lifecycle and informing decision-making processes.[28]

Furthermore, digital shadows can be leveraged in conjunction with other data-driven tools, such as predictive analytics and machine learning algorithms, to uncover hidden insights, forecast future trends, and optimize the performance and reliability of physical systems. By integrating digital shadows into a comprehensive data management and analysis framework, organizations can gain a competitive advantage through enhanced visibility, improved decision-making, and the ability to anticipate and respond to potential challenges before they arise.[28]

In essence, digital shadows play a vital role in the digital transformation of industries, enabling a deeper understanding of physical systems, driving continuous improvement, and facilitating the transition towards more proactive and data-driven approaches to asset management and operational optimization.[28]

I.4 Learning factories

Learning factories are advanced educational and training environments that replicate real-world industrial settings, providing hands-on experience with modern manufacturing processes, technologies, and systems. These environments are designed to bridge the gap between theoretical knowledge and practical application, enabling learners to engage in authentic production tasks, experiment with new technologies, and solve real-world problems.

Learning factories typically encompass a wide range of equipment, tools, and digital technologies found in contemporary industrial settings, such as CNC machines, robots, IoT devices, sensors, and simulation software. They are often integrated with cutting-edge concepts like Industry 4.0, Lean Manufacturing, and Digital Twins, creating a comprehensive learning ecosystem that reflects the complexities and challenges of modern manufacturing [2]

I.4.1 Domains of Application

Learning factories can be utilized in various domains, including but not limited to:

- **Manufacturing**: Offering practical training in advanced manufacturing techniques, process optimization, quality control, and the integration of digital technologies.
- **Automation and Robotics**: Providing experience with the programming, operation, and maintenance of robotic systems and automated production lines.
- **Industry 4.0**: Enabling learners to explore the integration of IoT, cyber-physical systems, big data analytics, and AI in manufacturing processes.
- **Lean Manufacturing**: Teaching principles and practices of lean production, including waste reduction, continuous improvement, and value stream mapping.
- **Supply Chain Management**: Simulating supply chain operations to enhance understanding of logistics, inventory management, and demand forecasting.
- **Product Design and Development**: Facilitating the design, prototyping, and testing of new products using advanced CAD/CAM tools and additive manufacturing technologies.[2]
- **Sustainability and Green Manufacturing**: Focusing on sustainable practices, energy efficiency, and environmental impact reduction in manufacturing processes.[2]
- **Healthcare**: Applying manufacturing principles to the production of medical devices, pharmaceuticals, and other healthcare-related products.[2]
- **Construction**: Simulating construction processes and the management of construction projects to improve efficiency, safety, and quality.[2]
- **Aerospace and Automotive**: Providing specialized training for the design, production, and maintenance of aerospace and automotive components and systems.[2]

I.4.2 Advantages

The learning factories brought lot of benefits in different domains (scientific, industrial, sustainability).

I.4.2.1 Hands-On Experience

Learning factories offer practical, hands-on training that helps learners develop skills and competencies required in real-world industrial environments. This experiential learning approach enhances understanding and retention of theoretical concepts.[39]

I.4.2.2 Bridging the Skills Gap

By providing access to modern equipment and technologies, learning factories help bridge the skills gap between academia and industry. They prepare students and professionals for the demands of contemporary manufacturing jobs.[39]

I.4.2.3 Innovation and Experimentation

Learning factories provide a safe and controlled environment for experimenting with new technologies, processes, and ideas. This fosters innovation and allows learners to test and refine their concepts before implementation in real production settings. [39]

I.4.2.4 Enhanced Collaboration

These environments encourage collaboration among students, researchers, and industry professionals. Collaborative projects and interdisciplinary learning help participants develop teamwork and communication skills.[39]

I.4.2.5 Industry-Relevant Curriculum

Learning factories often work closely with industry partners to ensure that the curriculum is aligned with current industry needs and standards. This relevance enhances the employability of graduates and the applicability of their skills.[39]

I.4.2.6 Simulation of Real-World Challenges

Learning factories replicate real-world industrial challenges, allowing learners to develop problem-solving and critical-thinking skills. They can work on complex, integrated projects that mimic actual production scenarios.[39]

I.4.2.7 Continuous Improvement

By incorporating Lean Manufacturing principles, learning factories teach the importance of continuous improvement and operational excellence. Learners can apply these principles to drive efficiency and quality in their future workplaces.[39]

I.4.2.8 Adaptation to Emerging Trends

Learning factories are designed to be adaptable, allowing for the integration of emerging technologies and trends. This ensures that learners are always exposed to the latest advancements in their fields.[39]

I.4.2.9 Sustainable Practices

Emphasizing sustainability, learning factories educate learners on eco-friendly manufacturing practices and the importance of reducing environmental impact. This knowledge is critical for developing sustainable industrial practices.[39]

I.4.2.10 Customized Learning Paths

Learning factories offer flexible learning paths tailored to the needs of different learners, whether they are students, professionals seeking upskilling, or researchers exploring new technologies.[39]

Figure I.3: Examples about learning factory: ErmaLean

Figure I.4: Examples about learning factories for industry 4.0 : CP lab

I.5 Industry 4.0

I.5.1 Definition

The Fourth Industrial Revolution, often referred to as Industry 4.0, is a remarkable transformation sweeping through traditional manufacturing and industrial practices. This pivotal shift is driven by the seamless integration of cutting-edge digital technologies, creating a new era of smart manufacturing.

At the heart of Industry 4.0 lies the fusion of the physical and digital realms, facilitated by the Internet of Things (IoT), cyber-physical systems (CPS), big data analytics, artificial intelligence (AI), and cloud computing. This convergence has ushered in a highly flexible, efficient, and responsive manufacturing environment, where real-time monitoring, optimization, and autonomous decision-making have become the norm.

Gone are the days of isolated, automated production. Industry 4.0 has ushered in a new paradigm of interconnected manufacturing systems, capable of adapting and optimizing themselves based on real-time data and insights. The result is a manufacturing landscape that is more agile, efficient, and responsive to market demands, empowering industries to stay ahead of the curve in an increasingly competitive global landscape.

This transformative shift is not merely a technological advancement; it represents a fundamental shift in the way we think about and approach industrial practices. By seamlessly blending the physical and digital realms, Industry 4.0 is paving the way for a future where manufacturers can harness the power of data and intelligent systems to drive innovation, enhance productivity, and deliver superior products and services to customers [29]

I.5.2 Aspects of Industry 4.0

Industry 4.0 encompasses several key aspects that collectively enhance the manufacturing firms:

I.5.2.1 Internet of Things (IoT)

The (IoT) refers to a network of physical objects, like devices, vehicles, and buildings, that have sensors, software, and other technologies as shown in I.6. These objects can connect and share data with other devices and systems over the internet. IoT allows information to flow seamlessly between the physical and digital worlds. This enables real-time data collection, monitoring, and management. In the context of Industry 4.0, IoT is important for creating smart factories. In these factories, machines and equipment can communicate with each other. This allows them to optimize production processes, reduce downtime, and improve efficiency. The connectivity of IoT enables advanced applications, such as predictive maintenance, real-time monitoring, and automated control of industrial systems.

Figure I.5: Illustration of the Internet of Things (IoT)

I.5.2.2 Cyber-Physical Systems (CPS)

The CPS are integrations of computation, networking, and physical processes. In CPS, embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. CPS are fundamental to the realization of Industry 4.0 as they enable the creation of smart systems that can autonomously coordinate and control industrial operations. These systems can include smart grids, autonomous vehicle systems, medical monitoring, industrial control systems, and robotic systems. CPS ensure real-time interaction between the digital and physical worlds, providing advanced capabilities such as self-optimization, self-configuration, and intelligent decision-making, which are essential for modern manufacturing environments.[30]

I.5.2.3 Big Data Analytics

Big Data Analytics refers to the process of examining large and varied data sets—termed big data—to uncover hidden patterns, unknown correlations, market trends, customer

Figure I.6: Illustration of the CPS

preferences, and other useful information that can help organizations make informed business decisions. In Industry 4.0, the vast amount of data generated by IoT devices, CPS, and other sources is analyzed using advanced analytics techniques such as machine learning, data mining, and statistical analysis. Big data analytics enables manufacturers to gain valuable insights into their operations, predict equipment failures, optimize production processes, and enhance supply chain management. By leveraging big data, companies can make data-driven decisions, improve operational efficiency, reduce costs, and drive innovation.[30]

I.5.2.4 Artificial Intelligence (AI) and Machine Learning (ML)

(AI) refers to the simulation of human intelligence processes by machines, particularly computer systems. These processes include learning (the acquisition of information and rules for using the information), reasoning (using rules to reach approximate or definite conclusions), and self-correction. Machine Learning (ML), a subset of AI, involves the development of algorithms that allow computers to learn from and make decisions based on data. In Industry 4.0, AI and ML are utilized to analyze large volumes of data generated by IoT devices and other sources, enabling the optimization of production processes, enhancement of product quality, and reduction of operational costs. These technologies facilitate predictive analytics, intelligent automation, anomaly detection, and advanced robotics, leading to smarter and more adaptable manufacturing systems.[30]

I.5.2.5 Cloud Computing

Cloud computing provides scalable and flexible computing resources, allowing manufacturers to store, process, and analyze data remotely. It facilitates real-time collaboration, data sharing, and access to advanced analytics tools, enhancing the overall agility and efficiency of manufacturing operations.[30]

I.5.2.6 Autonomous Robots

Autonomous robots are intelligent machines capable of performing tasks without human intervention. In Industry 4.0, these robots work collaboratively with human workers and other machines, increasing productivity, reducing labor costs, and improving workplace safety.[30]

I.5.2.7 Augmented Reality (AR) and Virtual Reality (VR)

AR and VR technologies enhance the manufacturing environment by providing immersive and interactive experiences. AR can overlay digital information onto the physical world, assisting with tasks such as assembly, maintenance, and training. VR creates simulated environments for product design, prototyping, and testing.[30]

I.5.2.8 Additive Manufacturing (3D Printing)

Additive manufacturing, or 3D printing, enables the creation of complex and customized products with high precision and minimal waste. Industry 4.0 leverages this technology for rapid prototyping, small-batch production, and the manufacture of intricate components that are difficult to produce using traditional methods.[30]

I.5.2.9 Digital Twin

A digital twin is a virtual model of a physical asset, process, or system. It continuously receives data from its physical counterpart, allowing for real-time monitoring, simulation, and optimization. [30]

I.5.2.10 System Integration

System integration involves the seamless connectivity and interoperability of various components within the manufacturing ecosystem. Industry 4.0 emphasizes horizontal and vertical integration, ensuring that all elements of the supply chain, from suppliers to customers, are interconnected and able to communicate effectively.[30]

I.5.2.11 Cybersecurity

With the increased connectivity and reliance on digital technologies, cybersecurity is a critical aspect of Industry 4.0. Protecting sensitive data, securing communication channels, and ensuring the integrity and availability of systems are essential to safeguard against cyber threats and ensure the smooth operation of smart manufacturing systems.[30]

I.6 Simulation

Simulation is an incredibly versatile technique that allows us to faithfully recreate and mimic the intricate workings of real-world processes, systems, and environments. By utilizing meticulously crafted models, whether mathematical, physical, or computational, we can create virtual representations that accurately capture the nuances and complexities of the actual systems.

These simulated environments offer us a powerful platform to analyze, experiment, and forecast outcomes without the constraints and risks inherent in dealing with real-world counterparts. Imagine being able to test the performance of a new aircraft design or the resilience of a city's infrastructure to natural disasters, all within the safety and control of a simulated setting. This ability to manipulate and observe these virtual scenarios in granular detail is truly transformative, unlocking insights and possibilities that would otherwise be impractical, if not outright impossible, to explore through direct experimentation.

Indeed, simulations have become indispensable tools for tackling the most complex and challenging systems that we encounter, showcasing their profound versatility and impact.

Simulation empowers us to explore solutions to challenges, regardless of their financial, operational, or moral complexities. This tool allows us to expand our knowledge and reach new horizons of discovery, while mitigating the risks and limitations that would otherwise hamper our advancements.

I.6.1 Offline Simulation

Simulations conducted separately from real-time operations, often called batch or non-real-time simulations, involve running models in a managed setting where the passage of time is uncoupled from actual events. This permits thorough investigation and testing without the demands of processing data in real-time. By decoupling the simulation from real-world constraints, researchers can explore scenarios and analyze outcomes in a more controlled manner.[1]

I.6.2 Advantages of Offline Simulation

- **Cost Savings**: Offline simulation reduces the need for physical prototypes and real-world testing, leading to significant cost savings in terms of materials, labor, and time.[12]
- **Risk Reduction**: By simulating potential scenarios and outcomes, organizations can identify and mitigate risks before implementing changes in the real system.
- **Flexibility**: Offline simulations can be easily modified and rerun with different parameters, allowing for extensive exploration of various scenarios and what-if analyses.[40]
- **Enhanced Understanding**: Simulations provide a visual and analytical understanding of system behavior, enabling better insights into complex processes and interactions.[40]
- **Optimization**: Through iterative experimentation, simulations help in optimizing system performance by identifying the best possible configurations and strategies.[12]
- **Training and Education**: Offline simulations are valuable tools for training personnel and educating students, providing hands-on experience in a safe and controlled environment.[5]

I.6.3 Domains of Application

- **Manufacturing**: Simulation is used to optimize production processes, layout planning, and supply chain logistics. It helps in improving efficiency, reducing waste, and increasing throughput.[38]

- **Healthcare**: In healthcare, simulations are employed for training medical professionals, planning surgical procedures, and modeling the spread of diseases for better preparedness and response.[38]

- **Aerospace and Defense**: Simulations assist in the design and testing of aircraft, spacecraft, and defense systems. They are crucial for mission planning, safety analysis, and performance optimization.[38]

- **Automotive**: The automotive industry uses simulations for vehicle design, crash testing, and performance analysis. It helps in reducing development time and improving safety and reliability.[38]

- **Energy**: In the energy sector, simulations are used for modeling power grids, optimizing energy production, and analyzing the impact of renewable energy sources on the grid.

- **Urban Planning**: Simulations aid in the design and management of urban infrastructure, traffic flow analysis, and disaster preparedness planning.[38]

- **Finance**: Financial institutions use simulations for risk assessment, portfolio management, and market analysis. It helps in predicting market trends and making informed investment decisions.[38]

- **Logistics and Supply Chain**: Simulation is used to optimize logistics operations, warehouse management, and supply chain strategies. It ensures efficient resource utilization and timely delivery of goods.[38]

- **Education and Training**: Educational institutions and training programs use simulations to provide immersive learning experiences, practical exercises, and virtual labs for students and trainees.[38]

- **Telecommunications**: In telecommunications, simulations help in network design, capacity planning, and performance analysis. It ensures reliable and efficient communication services.[38]

I.7 Flexsim simulation software

FlexSim is a remarkable simulation software that empowers users to model, analyze, visualize, and optimize a wide range of systems and processes. This powerful yet user-friendly tool has found its way into diverse industries, from manufacturing and healthcare to logistics and warehousing. By creating realistic simulations, FlexSim enables companies to make informed decisions, enhance their processes, and drive operational efficiency.[31]

Crafted with versatility in mind, FlexSim allows users to tackle complex challenges with ease. Whether you're optimizing a production line, streamlining a healthcare workflow, or enhancing a logistics network, this software provides the tools and capabilities to bring your ideas to life. Its intuitive interface and robust modeling capabilities make it accessible to users of all skill levels, empowering them to explore innovative solutions and unlock new levels of performance.[7]

At the heart of FlexSim lies a commitment to helping organizations thrive in an ever-evolving business landscape. By offering a seamless blend of powerful simulation, data analysis, and visualization features, this software equips professionals with the insights they need to make data-driven decisions, identify areas for improvement, and ultimately, achieve their operational goals.[7]

I.7.1 What can we do with Flexsim?

3D Modeling and Visualization

FlexSim provides an intuitive 3D modeling environment where users can create detailed, realistic models of their systems like we have shown in III.1 . The 3D visualization helps stakeholders understand complex processes and identify potential issues.[31]

Figure I.7: 3D simulation

Drag-and-Drop Interface

The software features a user-friendly drag-and-drop interface, allowing users to quickly and easily build simulation models without requiring extensive programming skills.

Object Library

FlexSim includes a comprehensive library of pre-built objects, such as conveyors, machines, vehicles, and workers. These objects can be customized to match the specific characteristics of the user's system.

Dynamic and Discrete Event Simulation

FlexSim supports dynamic simulation, which allows for the modeling of time-dependent processes, and discrete event simulation, which focuses on the occurrence of specific events and their impact on the system.

Real-Time Data Integration

The software can integrate with real-time data sources, such as IoT devices, sensors, and enterprise systems, to create simulations based on current operational data.[31]

Statistical Analysis and Reporting

FlexSim offers powerful statistical analysis tools to evaluate the performance of different scenarios. Users can generate detailed reports and visualizations to support data-driven decision-making.[31]

Optimization Tools

Built-in optimization tools enable users to explore different configurations and find the best solutions for improving system performance, reducing costs, and increasing efficiency.[31]

Scalability and Flexibility

FlexSim is scalable and can handle simulations of varying complexity, from small-scale processes to large, intricate systems. Its flexibility allows users to model a wide range of applications across different industries.[31]

Applications of FlexSim

Manufacturing

FlexSim is extensively used in manufacturing to simulate production lines, assembly processes, and material handling systems. It helps manufacturers identify bottlenecks, optimize resource allocation, and improve production efficiency. By modeling production processes, manufacturers can test changes to workflows, machinery, and staffing before implementing them in the real world, thereby reducing risks and costs associated with trial-and-error approaches.[31]

Healthcare

In healthcare, FlexSim is used to model patient flow, staff scheduling, and facility layout as it is visible in III.2 . It aids healthcare providers in improving patient care, reducing wait times, and optimizing the utilization of resources.[32]

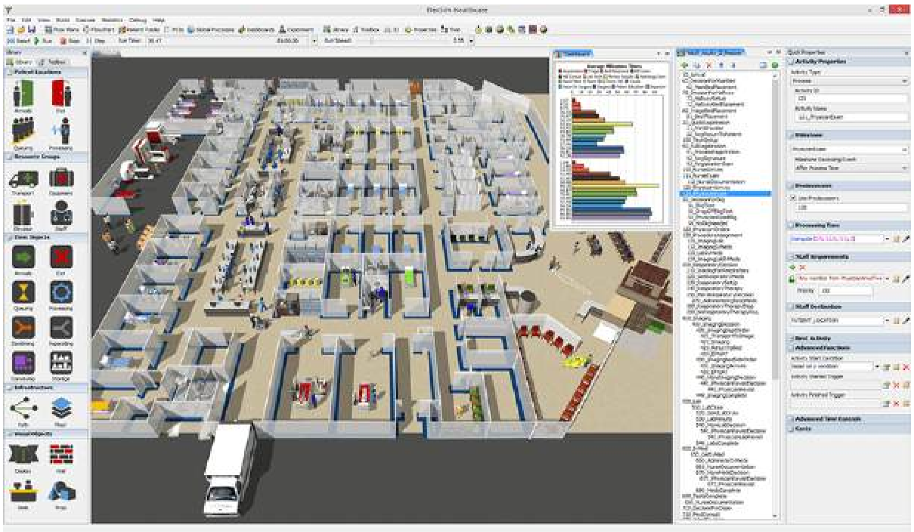

Figure I.8: Healthcare simulation using Flexsim

I.7.1.1 Big Data Analytics

Logistics and Warehousing

FlexSim can simulate warehouse operations, distribution networks, and transportation systems. It helps logistics companies enhance inventory management, streamline supply chains, and improve delivery performance. By analyzing different logistical strategies and operational adjustments in a virtual environment, companies can enhance efficiency, reduce costs, and respond more effectively to market demands.

Supply Chain Management

The software is also used to model and analyze entire supply chains, from raw material sourcing to finished product delivery. It supports decision-making related to supplier selection, inventory levels, and distribution strategies.[31]

Service Industries

FlexSim is applicable in service industries such as retail, hospitality, and banking, where it can simulate customer service processes, staff allocation, and facility layouts to improve service quality and operational efficiency.

Advantages of Using FlexSim

Improved Decision-Making

FlexSim provides a virtual environment where users can test different scenarios and predict the outcomes of their decisions, leading to more informed and effective decision-making.[26]

Cost Reduction

By identifying inefficiencies and optimizing processes, FlexSim helps organizations reduce operational costs, minimize waste, and improve overall profitability.[26]

Risk Mitigation

Simulation allows users to evaluate the impact of changes without disrupting actual operations, reducing the risk associated with implementing new strategies or technologies.

Enhanced Collaboration

The 3D visualization and reporting features facilitate communication and collaboration among stakeholders, enabling them to understand and address complex issues collectively.[31]

Increased Efficiency

FlexSim enables the optimization of resource utilization, process flow, and system performance, leading to increased efficiency and productivity.[26]

Scalability

FlexSim can handle simulations of varying complexity, from small-scale processes to large, intricate systems, making it suitable for a wide range of applications.[26]

Flexibility

The software is highly flexible, allowing users to innovate and improve models and also to model a wide range of applications across different industry applications.[31]

I.8 Lean manufacturing

The methodology of Lean Manufacturing has gained immense popularity in production management due to its systematic approach that prioritizes customer value while minimizing waste. Developed from the Toyota Production System (TPS), Lean Manufacturing emphasizes continuous process improvement and the elimination of non-value-added activities, also known as (muda). These activities include overproduction, waiting, inventory, motion, transportation, rework/defects, and over-processing. The goal of Lean Manufacturing is to streamline workflows and increase productivity by prioritizing these principles.[41]

The main objective of Lean Manufacturing is to reduce waste and increase efficiency. It is achieved through the implementation of various techniques and principles such as defining value from the customer's perspective, mapping value streams, establishing continuous flow, implementing pull systems, and striving for perfection. By applying these principles, Lean Manufacturing aims to make operations more agile, flexible, and responsive to market needs.

One of the key principles of Lean Manufacturing is defining value from the customer's perspective. This principle emphasizes the importance of understanding the customer's needs and requirements. By identifying what the customer values, organizations can focus on delivering products and services that meet those needs, thus increasing customer satisfaction[15].

Another important principle of Lean Manufacturing is mapping value streams. This principle involves identifying all the steps involved in the production process and analyzing them to determine which steps add value and which do not. By eliminating non-value-added activities, organizations can reduce waste and increase efficiency.[14]

Establishing continuous flow is also a crucial principle of Lean Manufacturing. This principle involves designing the production process in such a way that products move seamlessly from one stage to another without any interruptions or delays. By establishing continuous flow, organizations can reduce lead times and increase productivity.

Implementing pull systems is another key principle of Lean Manufacturing. This principle involves producing only what is needed when it is needed. By implementing pull systems, organizations can reduce inventory and minimize waste.[14]

Finally, Lean Manufacturing strives for perfection. This principle emphasizes the importance of continuously improving processes to eliminate waste and increase efficiency. By constantly striving for perfection, organizations can achieve higher levels of productivity, quality, and customer satisfaction.[14]

Lean Manufacturing is a methodology that has proven to be highly effective in maximizing customer value while minimizing waste. By following key principles such as defining value from the customer's perspective, mapping value streams, establishing continuous flow, implementing pull systems, and striving for perfection, organizations can achieve higher levels of efficiency and productivity.[14]

I.8.1 muda

The elimination of muda, a fundamental principle in lean manufacturing, pertains to any procedure or operation that consumes resources without providing any value to the final product or service from the customer's point of view. Muda comprises seven types of waste as we can see in I.9 including overproduction, waiting, transportation, unnecessary processing, inventory, motion, and defects.[33]

1-**Overproduction**:
Producing more than what is needed or producing it too early. Excess inventory is generated, which ties up resources and raises storage costs.

2-**Waiting**:
The use of resources (such as workers, machines, and materials) in a productive manner is what causes idle time. This includes waiting for materials, equipment, or information.

3-**Transport**:
The eradication of muda leads to increased efficiency, decreased expenses, and improved productivity and customer fulfillment.

4-**Extra-processing**:
Engaging in activities that exceed the customer's needs or expectations, such as incorporating unnecessary steps into the production process, over-complicating designs, or implementing duplicate procedures.

5-**Inventory**:
Inventory that is surplus to immediate requirements consists of raw materials, work-

in-progress, and finished goods. This unnecessary inventory not only occupies valuable storage space but also ties up capital. Additionally, it can mask production inefficiencies and imperfections.

6-**Motion** :

Unneeded actions carried out by employees or equipment, such as unnecessary walking, stretching, or stooping. These actions may cause weariness or harm and also result in ineffectiveness in the task.

7-**Defects**:

Defects are products and services that lack desired quality standards, hence failing to meet customer expectations. Examples of this type of waste include rework, scrap, and returns. To be more specific, defects stand for material, energy, time, and labor wastage; they also symbolize a dissatisfied customer base and harm to the reputation of the organization. The defects can be addressed by finding the root causes through quality control measures to ensure such flaws never happen again [**?**].

There are two other wastes, **the wasted potential of people** because Under-utilizing the skills and talents of employees leads to missed opportunities for improvement and innovation and **Environmental Waste** which is concentrated in any activity that causes harm to the environment, such as excessive use of resources, energy waste, and pollution [16].

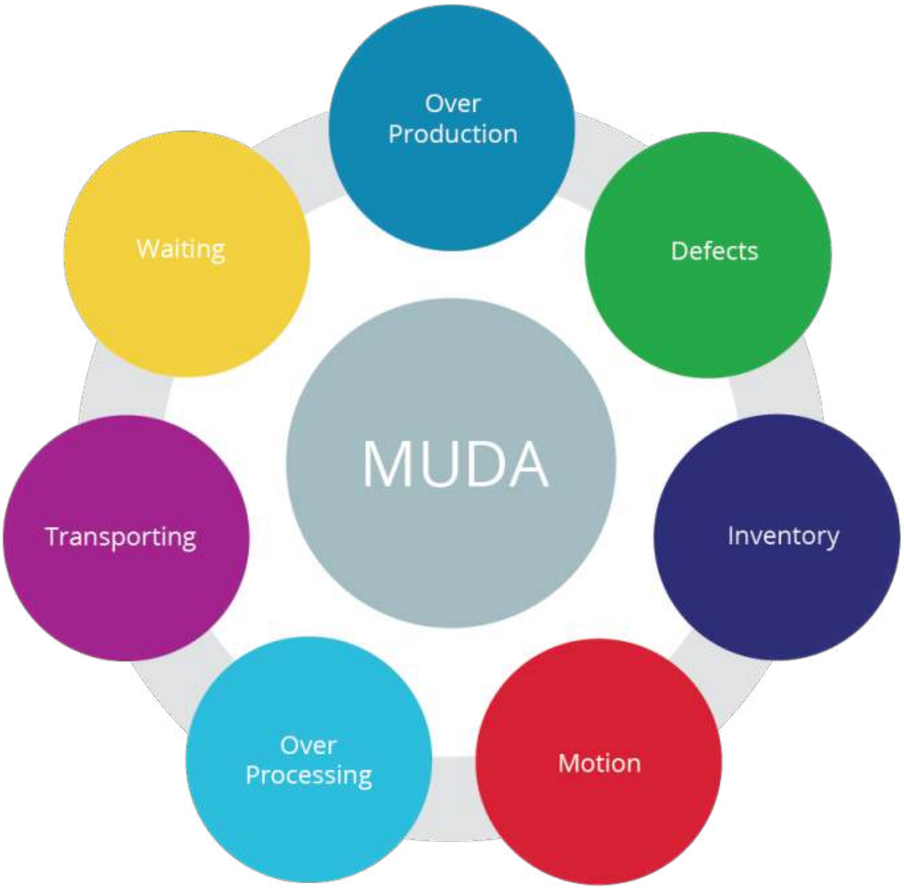

Figure I.9: 7 muda

Additionally as shown in I.10, there is a wide array of methods and tools in this field. Here, we will highlight some of the key ones:

I.8.2 5S

The 5S methodology is a systematic approach to workplace organization and standardization, originating from Japanese manufacturing practices [34]. It consists of five phases, each represented by a Japanese term starting with the letter "S":

- **Seiri (Sort)**: Remove unnecessary items from the workplace to eliminate clutter and improve efficiency.
- **Seiton (Set in Order)**: Arrange necessary items in a logical order for easy access and use.
- **Seiso (Shine)**: Clean the workplace and equipment regularly to maintain a neat and tidy environment.
- **Seiketsu (Standardize)**: Establish standardized procedures and schedules to maintain organization and cleanliness.
- **Shitsuke (Sustain)**: Foster a culture of continuous improvement and discipline to sustain the 5S practices.

I.8.3 Kaizen

Kaizen is a Japanese term meaning "continuous improvement." It refers to the philosophy and practices that focus on incremental improvements in processes, products, or services over time. The Kaizen methodology emphasizes employee involvement at all levels, encouraging them to suggest and implement small, incremental changes that collectively result in significant improvements. The main principles of Kaizen include[13] :

- **Continuous Improvement**: Ongoing effort to improve products, services, or processes.
- **Employee Involvement**: Engagement and participation of all employees in the improvement process.
- **Standardization**: Establishing and maintaining standards to ensure consistency and quality.
- **Customer Focus**: Prioritizing the needs and satisfaction of customers in all improvement efforts.

I.8.4 Jidoka

Jidoka, also known as "autonomation," is a principle in lean manufacturing that emphasizes the automation of processes with a human touch. It involves equipping machines and production lines with the ability to detect abnormalities or defects and automatically stop operations to prevent the production of defective products. The main objectives of Jidoka are[11]:

- **Defect Prevention**: Detect and address defects at the source to prevent their propagation.
- **Quality Control**: Ensure that only high-quality products are produced.
- **Empowerment**: Enable operators to focus on problem-solving and improvement rather than merely monitoring machines.

I.8.5 Standard Work

Standard Work refers to the practice of establishing and documenting the most efficient methods and sequences for performing tasks. It serves as a foundation for continuous improvement and ensures consistency, safety, and quality in operations. The key components of Standard Work include:

- **Takt Time**: The pace at which products must be produced to meet customer demand.
- **Work Sequence**: The specific order in which tasks should be performed.
- **Standard Inventory**: The minimum amount of materials or parts required to keep the process running smoothly.

I.8.6 Heijunka

Heijunka, or production leveling, is a technique used in lean manufacturing to reduce the unevenness in production. It involves smoothing out the production schedule by distributing the workload evenly across all processes over a given period [10]. The goals of Heijunka are:

- **Reduce Overburden**: Avoid overloading workers and equipment.
- **Minimize Inventory**: Reduce the need for excess inventory by leveling production.
- **Enhance Flexibility**: Improve the ability to respond to changes in customer demand.

I.8.7 Kanban

Kanban is a visual scheduling system used in lean manufacturing to control the flow of work and materials. It utilizes cards or signals to represent tasks or items and their movement through the production process[3]. The key benefits of Kanban include:

- **Visual Management**: Enhance visibility and transparency of work in progress.
- **Work in Progress (WIP) Limits**: Control the amount of work in progress to prevent bottlenecks.
- **Continuous Flow**: Promote a smooth and continuous flow of work through the production system.
- **Just-in-Time (JIT)**: Ensure materials and products are delivered exactly when needed.

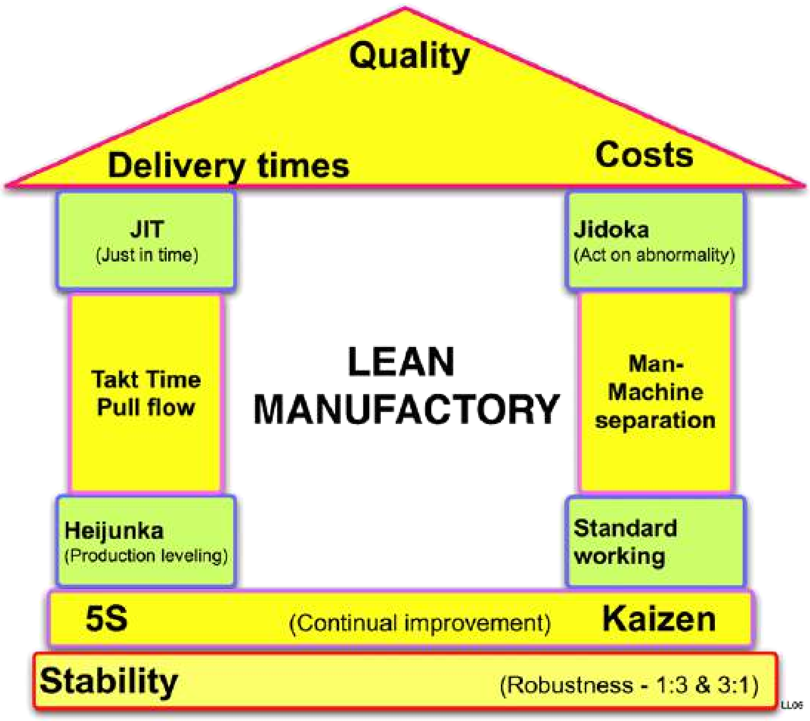

Figure I.10: Lean manufacturing aspects

In the definition chapter of this dissertation, we extensively explored key aspects and insights within the domain of digital twins. We delved into fundamental concepts, elucidating the core principles and applications that underpin this innovative technology. By examining various perspectives and emerging trends, we gained a comprehensive understanding of how digital twins are transforming industries, optimizing processes, and enhancing decision-making capabilities.

Chapter II

ErmaLean Learning Factory: Bridging Theory and Practice in Modern Manufacturing

Introduction

Learning factories are specialized educational environments that have been meticulously designed to offer students a unique and immersive learning experience in the field of manufacturing and production processes. These cutting-edge facilities not only enhance technical skills but also foster critical thinking and problem-solving abilities, empowering learners to innovate and improve processes continuously.

At the core of a learning factory lies the replication of real-world industrial settings, creating by that a warm engaging environment for student to enhance their skills and professional refection. Equipped with basic tools, and different softwares, these facilities enable learners to directly apply the principles and methodologies they have studied, such as Lean manufacturing, Six Sigma, and Industry 4.0 concepts. This hands-on approach fosters a deeper understanding of operational excellence, process optimization, and digital transformation, crucial elements for success in the modern manufacturing firms.

By providing a controlled space, yet realistic, setting, learning factories empower students to experiment, troubleshoot, and problem-solve in a safe and supportive environment. Instructors and industry experts work closely with learners, offering guidance and feedback to ensure that the knowledge gained is directly applicable to real-world scenarios. This iterative process not only enhances technical proficiency but also cultivates critical thinking, decision-making, and collaboration skills – attributes highly sought after by employers in the manufacturing sector.

Learning factories present a vibrant connection between educational institutions and industries, enabling valuable partnerships and joint efforts. Businesses and universities work together to address complex challenges. Industry professionals and topic specialists are making programs, ensuring that learning side keeps pace with the changing demands and advancements in manufacturing. This dynamic collaboration empowers learners to stay at the forefront, developing the essential skills and expertise to succeed in the rapidly evolving technological realm.

Figure II.1: ErmaLean

II.1 Definition of the ErmaLean

ErmaLean is a cutting-edge learning factory that combines Lean Six Sigma principles with Industry 4.0 digital technologies. It provides a comprehensive learning experience in a realistic industrial setting where learners can engage in continuous improvement activities.[35]

At the core of ErmaLean is a carefully designed manufacturing system that mimics real industrial workflows, processes, and challenges. Learners apply their knowledge and skills in a hands-on, dynamic environment, gaining practical experience that connects the gap between theory and real-world application.The goal from this learning factory, is how to teach students the Lean manufacturing and its insights using this novel method of learning.[35]

The facility is equipped with advanced digital technologies, such as IoT sensors, automated data collection systems, and analytics platforms. These tools allow learners to use Industry 4.0 technologies to gather, analyze, and interpret data in real-time, identifying opportunities for optimization and continuous improvement.[35]

This learning factory, incorporates classroom instruction, interactive simulations, and hands-on workshops to teach Lean Six Sigma and Lean manufacturing principles. Learners explore process mapping, root cause analysis, mistake-proofing techniques, and data-driven decision-making while navigating a dynamic manufacturing environment.

Industry experts and industry professionals mentor learners, offering guidance and insights. This collaborative approach fosters knowledge-sharing and continuous learning, preparing participants for the demands of modern manufacturing.[36]

By integrating Lean Six Sigma and Industry 4.0 technologies, ErmaLean sets a new standard for industrial learning, it equips future manufacturing leaders with the skills, knowledge, and practical experience needed to drive innovation, enhance efficiency, and stay competitive in the global market and the most important thing ErmaLean is one of the few learning factories that teaches the learners the importance of taking the good decision especially with the integration of the Lean manufacturing discipline, learner will gain a crucial skill in every industry different hierarchical levels which is the decision making .[36]

II.2 Components and Structure of ErmaLean

ErmaLean is composed of 5 evolutionary manual assembly stations, parts storage warehouse and a supervision post,the didactic line comprises other elements, as well, such as a supervision station shown in Figure II.3 , and trolleys for transportation of raw materials, work-in-progress, and finished products as illustrated in Figure II.2. The line supports digital management as it is fitted with Tulip software that is integrated with ease at every assembly station and very key in enhancing information flow by providing detailed steps to human operators on assembly, placement of tools, and organization of the workstation. This is very key to efficiency optimization in operations. regarding to its flexibility, this line can take different shapes as we can see in II.5 referring to the L-shaped layout and in II.3 referring to the U-shaped layout. These implementations mode gives us more cases to adopt, we can compare between the two modes we can create several practical spans scenarios.[35]

Figure II.2: trolleys

Figure II.3: Supervision post

II.2.1 Assembly stations

The assembly station is built to ensure efficient and adaptable operations. There are 5 workstations, each equipped with wheels for easy reconfiguration of the layout[28]. Each workstation includes the following elements:

1. A reversible work surface with a smooth side and a side equipped with pallet retention slots and grooves for positioning component box supports at an ergonomic angle, enhancing label visibility and small component handling (Ergonomics scenario).
2. Ergonomic LED lighting with anti-glare covers for operator comfort.
3. Under each work surface, an RFID reader detects pallet presence at the workstation. Each entry and exit at a workstation is recorded in the "Time at Stations". RFID reader information is transmitted via the IO-Link master to the Tulip Edge unit.
4. A lower area for component box supply and empty box disposal, equipped with label holders (Visual Management scenario).
5. A storage drawer for small tools under the work surface (5S scenario).
6. A reject bin (red box) to isolate non-conforming parts, equipped with an opening detector. Opening the box triggers a reject declaration window display if screens connected to TULIP are in use (=¿ Quality scenario).
7. A removable Andon. Control of the 3 cylinders is done via the selector button when not using the operator's digital assistance environment (Tulip). When using the Tulip interface, display control (green; orange; red) is based on the operator's manipulations on the workstation screen display (Visual Management scenario).
8. Each workstation is equipped with 3 document holders (process sheets; instructions...). These holders are removable and can be replaced with a PC screen connected to the

TULIP software, positioned in place of the document holders (Visual Management scenario).

9. A groan-box board for KANBAN labels can be positioned on the left post uprights. It is used for Kanban supply management, dividing operations into two subprocesses. Removable tabs (green; yellow; red) are used to visually indicate replenishment needs. A label printing file is available.

10. Ergonomic chairs, with various designs to match each operator's morphology, are provided for testing (Ergonomics scenario).

11. A label printer is also included to equip one of the workstations. It allows for product identification with serial numbers. These labels are affixed to each product for identification purposes. The serial number is generated by the TULIP software each time a pallet passes through workstation 1. For printer usage, refer to the usage document.

As we can see in II.6 the difference between a simple configuration of the station and the configuration 4.0 using Tulip software

Remark: L'Andon is an alarm system that allows an operator to signal when encountering an anomaly at their workstation.

II.2.1.1 Control quality post

In addition to the necessary equipment at every production workstation, one specific station can be set up as a "networked quality control station" as referred in II.7. This specialized station can include the following elements: a networked power supply, which can be managed through the "Tulip" software to test the assembled gear motor under different scenarios and confirm its proper operation on the "Electrical Measurement Bench for Gear Motor"; a networked caliper to complete the mechanical assembly compliance check; an industrial vision control module with AI (not part of this setup) for automated inspection tasks; a set of augmented reality glasses (not part of this setup) to assist operators and support maintenance activities; and a collaborative robot (not part of this setup).[28]

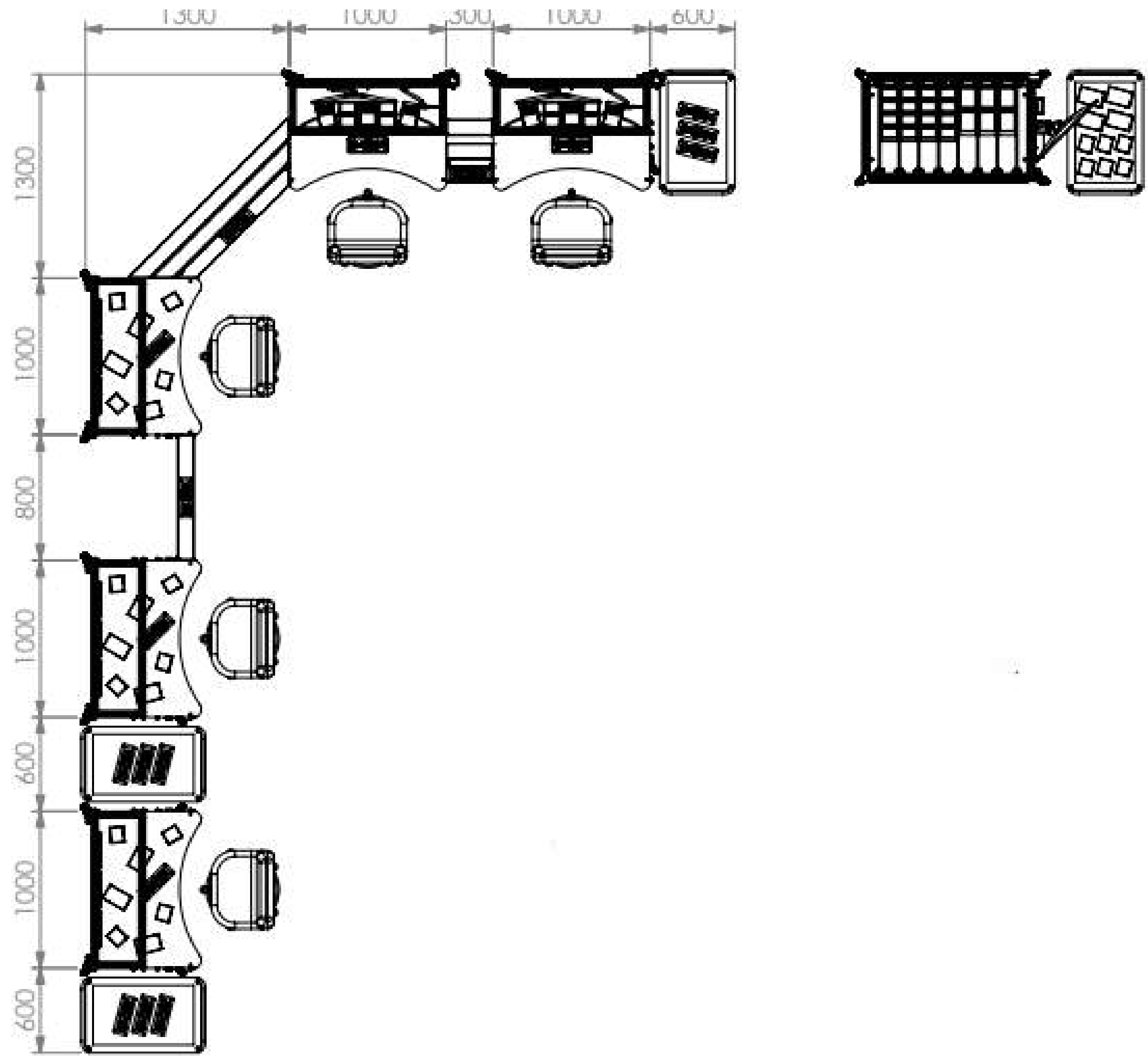

Figure II.4: Spatial Layout in L-shaped Learning Factory

Figure II.5: Spatial Layout in U-shaped Learning Factory

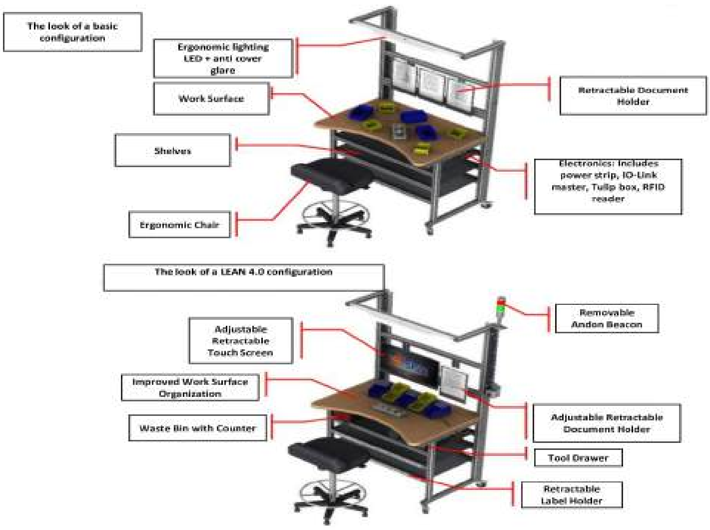

Figure II.6: Basic configuration vs Lean 4.0 configuration

Figure II.7: networked quality control station

II.2.2 The Warehouse

The warehouse, as its name suggests, is designed to store parts by reference (manufactured parts and standard components) that will be used for assembling the different variants of the gear motor (0.197, 0.213, and 0.218) [28].

As shown in II.8 it features four gravity-fed shelves to ensure FIFO (First In, First Out) consumption of components and a top shelf for the return of empty containers and finished products. This storage unit can accommodate two types of bins:

- 1-liter blue bins (3 per row)
- 0.3-liter yellow bins (6 per row)

Entry Side Identification:

- Labels are in place with the assigned codes, product reference, designation, and supplier.

Exit Side Identification:

- Labels are in place with the assigned codes, product reference, and designation.

The storage unit is equipped with a pick-to-light system for efficiently managing the entry and exit of components. Component transactions are recorded using a QR code scanner on the labels of the bins.

Implementing QR code scanning technology at this station highlights the advantages and drawbacks of QR code technology compared to the RFID technology used at other stations, providing a comprehensive understanding of both systems' effectiveness in a learning factory environment.

II.2.2.1 Basic Version of the Warehouse

It is the basic version of the warehouse, the warehouse includes the following elements to allow the operator to stock and destock component bins:

- A power socket block for the electrical supply of the warehouse
- A shelf for the quick return of empty bins and finished products
- Four gravity-fed shelves for storing component bins
- Label holders on the entry side of the warehouse
- Label holders on the exit side of the warehouse
- Labels with assigned codes: product reference and designation on both the entry and exit sides
- Two supports for hanging paper documents (inventory, instructions, part references, etc.)
- A Tulip Gateway (not used in this version of the warehouse)

Figure II.8: Illustration of a digitally-enabled Warehouse 4.0 featuring RFID technology

- A light kit box (not used in this version of the warehouse)
- LED strips on both the entry and exit sides (not used in this version of the warehouse)
- Two sensors: a temperature sensor and a humidity sensor (not used in this version of the warehouse)
- A barcode scanner (not used in this version of the warehouse)
- A Wi-Fi repeater to connect the Tulip Gateway to an internet connection (not used in this version of the warehouse)

This warehouse layout is designed to efficiently manage the flow of goods, making it easy for operators to handle stocking and unstocking tasks. The straightforward and user-friendly design ensures that all necessary components are readily accessible, minimizing downtime and disruptions during the work process. Moreover, this setup is not just a solution for today's needs; it is strategically planned to adapt to future requirements. The modular nature of the configuration allows for seamless integration of new technologies, such as automated guided vehicles, advanced inventory management systems, and real-time data analytics. This flexibility ensures that the warehouse can evolve alongside the advancements in manufacturing and logistics, maintaining its efficiency and effectiveness over the long term. In summary, this warehouse layout combines simplicity and sophistication, providing a robust foundation for current operations while being prepared to incorporate cutting-edge innovations as they become available.

The production process is flexible, able to adjust to the ever-changing requirements of a contemporary educational setting. It can effectively respond to the diverse and evolving needs of a modern learning facility.

II.2.2.2 Warehouse in LEAN 4.0 Version

In the LEAN 4.0 version, several elements are added to facilitate the operator's stocking and destocking of component bins. Below are the features included in the LEAN version of the warehouse:

- A power socket block for the electrical supply of the warehouse
- A shelf for the quick return of empty bins and finished products
- Four gravity-fed shelves for storing component bins
- Label holders on the entry side of the warehouse
- Label holders on the exit side of the warehouse
- Labels with assigned codes: product reference and designation on both the entry and exit sides
- A removable, height-adjustable touch screen PC
- A Tulip Gateway
- A light kit box to illuminate LEDs upon reading a QR code
- LED strips on both the entry and exit sides to guide the operator to the relevant row as shown in II.9
- Two sensors: a temperature sensor and a humidity sensor
- A barcode scanner for scanning the QR codes of components to be processed
- A Wi-Fi repeater to connect the Tulip Gateway to an internet connection

This cutting-edge configuration significantly boosts the operator's productivity by seamlessly blending state-of-the-art digital tools and advanced automation technologies. By optimizing the stocking and unstocking procedures, it ensures smooth operations with minimal manual intervention, embracing the principles of a LEAN 4.0 environment. The integration of these advanced technologies transforms the warehouse into a highly responsive and adaptable space. Real-time data collection and analysis enable precise inventory management, reducing waste and ensuring the availability of components exactly when needed. This level of efficiency not only accelerates the workflow but also diminishes the likelihood of errors, contributing to higher quality outcomes. User-friendly digital interfaces, such as the touch screen PC and the Tulip Gateway, provide operators with intuitive platforms to manage their tasks. These tools offer immediate access to essential information, instructions, and real-time updates, streamlining decision-making processes and enhancing overall productivity.[37] Furthermore, the incorporation of automation elements, like the pick-to-light system and QR code scanning, reduces the physical and cognitive burden on operators. These technologies guide operators through their tasks with precision, ensuring each step is carried out accurately and efficiently. Moreover, the integrating LEAN 4.0 into warehouse operations doesn't just improve efficiency, but also plays a crucial role in the comprehensive digital transformation of manufacturing. By adopting digital technologies like IoT sensors, RFID systems, and automated analytics, the warehouse becomes a vital component of Industry 4.0. Real-time data insights from the warehouse floor enable predictive maintenance, optimize inventory, and support agile decision-making across the production line. This digital integration enhances responsiveness to market demands and fosters a more interconnected and adaptable manufacturing ecosystem. Embracing LEAN 4.0 principles firmly positions the warehouse as a foundational element in the transition to Industry 4.0, driving continuous improvement and innovation within the modern learning factory.[37]

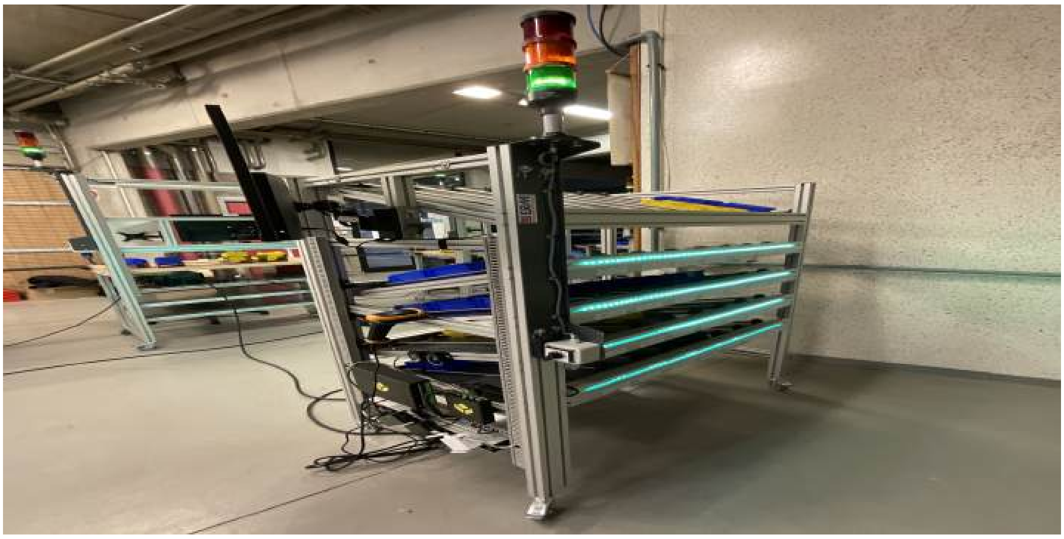

Figure II.9: Visualization of LED strip guidance system in a Warehouse 4.0

II.2.3 Peripheral Stations

II.2.3.1 Handling with Trolleys

A three-tier trolley is utilized for supplying workstations II.10, featuring perimeter-equipped trays for positioning identification labels on component boxes or recipient stations. Labels for these trays are provided in the technical file annexes for printing purposes, contributing to Visual Management (VM) and 5S principles.

Four 2-tier trolleys are employed for transferring products between stations in a push-flow configuration. The ample surface area of these trolleys allows for the storage of multiple pallets, reducing errors and ensuring adherence to FIFO (First In, First Out) principles.[35]

Additionally, two two-tier trolleys II.11 serve as entry and exit points for line pallet transfers. In a KANBAN setup, these trolleys facilitate product transfer between sub-processes.

Figure II.10: 3-tier trolley

Figure II.11: 2-tier trolley

II.2.3.2 Option - Industrial Vision Kit (not included in this proposal)

The Industrial Vision Kit can be integrated into connected stations to perform automated inspection tasks. It includes specific supports, necessary connectivity for integration (on the connected station), an intelligent industrial camera, and a 3D camera. Two industrial software programs accompany this hardware for camera programming.

This kit enables various operations, including part presence detection, object detection, counting, assembly verification, shape/profile detection, and more. It can also operate independently for vision-based activities. We provide several educational activities on vision applications, such as shape detection, part measurement, BLOB analysis, and more.[8]

II.2.4 Management Station

The management station, also referred to as the "supervisory PC," serves as the operational hub of the ErmaLean learning factory. It consists of a dedicated PC that allows configuration, visualization, and efficient management of all operations on the production line through the Tulip software environment. This station plays a crucial role by providing a comprehensive and interactive dashboard essential for optimal management and continuous monitoring of manufacturing activities.

Key functionalities of the management station include:

- Real-time monitoring of the status of each Work Order (WO), providing visibility into the progress and status of each production batch.
- Monitoring critical events throughout the production process, facilitating early detection of issues and immediate corrective actions.
- Analysis of production times to assess operational performance and identify opportunities for efficiency improvement.
- Continuous quality control to ensure product compliance with required standards and specifications, using real-time data.
- Detailed tracking of the specific assembly stage where each operator is working, enabling fine-grained resource management and efficient task allocation.
- Proactive management of stock levels to optimize inventory levels and prevent potential stockouts.
- Comprehensive monitoring of defect history and blocking states, supporting retrospective analysis and continuous process improvement.

In addition to these operational functionalities, the management station is equipped with a set of displayed documents to materialize the "factory cockpit." These documents include examples of dashboards and KPI (Key Performance Indicator) tracking reports, essential for evaluating the overall performance of the factory and guiding strategic decisions.

This centralized station represents not only an advanced control interface but also a powerful tool for proactive management and effective direction of the ErmaLean factory, thereby supporting continued commitment to operational excellence and innovation in the modern manufacturing sector.

II.2.5 Production Line Layouts

The ErmaLean line allows for diverse manufacturing processes, referred to as flows. Each flow has unique specifications and materials that vary from one production run to the next. A critical parameter that greatly affects these flows is the layout of the line before initiating the planned production. This parameter greatly influences the movement of information, materials, and personnel. Therefore, the decision-making process will consider the identified developments and their associated impacts. The following subsection will outline the various layout options available on this line. But before that we have to cite briefly the production ranges proposed by the ERM team

II.2.5.1 Flow Type A: Push Flow Organization

The Flow Type A is designed for a push flow organization. - Scheduling by Manufacturing Order

The production run using this flow type aims to create significant work-in-progress (WIP) inventory. This approach intentionally generates imbalances between workstations to highlight inefficiencies and bottlenecks in the production process. By doing so, it allows for the identification and analysis of areas that require improvement, enabling a better understanding of how to streamline operations and reduce waste.

II.2.5.2 Workshop Organization for Flow Type B

The Flow Type B approach is tailored for organizations prioritizing a flexible, responsive supply chain. By incorporating insights gained from the initial Flow Type A evaluation, this method strives to enhance customer service by minimizing order fulfillment times. For optimal outcomes, it's advised to implement this flow under the guidance of TULIP supervision. The production line's U-shaped layout promotes seamless workflow and open communication among team members.

II.2.5.3 Workshop Organization for Flow Type C

The Flow Type C approach is tailored for a pull-based workflow, leveraging a KANBAN system to manage the materials moving between workstations 2 and 3. This design incorporates the enhancements identified during the initial analysis of Flow Type A. The goal of this production flow is to minimize the time it takes to fulfill customer orders, ultimately enhancing the service rate. For the best outcomes, it is advised to implement this flow under the guidance of TULIP supervision. The production line is structured in a U-shape, with a designated distance maintained between workstations 2 and 3 to accommodate the KANBAN system effectively.

II.2.5.4 Workshop Organization for Flow Type D

For a pull-based manufacturing approach, Flow Type D is designed to integrate product customization as late as feasible in the production process. By delaying standardization, this flow builds upon insights gained from the initial Flow Type A evaluation, aiming to minimize work-in-progress stocks. For optimal outcomes, TULIP oversight is advised. The production line can be configured linearly or in a U-shaped layout, tailored to the specific needs and constraints of the manufacturing setting.

As we have seen in the previous texts, the learning line a very flexible in the layout domain we can have many line configurations (L-shaped, U-shaped, parallel...). To explore more the possible layout of this line. we will see more details this in the following paragraphs.

II.2.5.5 Implementation in Line

The Implementation in Line, also known as an I-line, refers to a straight-line arrangement of the production system as shown in II.12 which refers to the different I-shaped implementations possible using trolleys and conveyors. This is one of the most standard and commonly used layouts for assembly lines. In this configuration, workstations and equipment are arranged in a direct, linear sequence. This setup offers several advantages and considerations:

- **Workflow Efficiency:** The I-line layout ensures a smooth and sequential flow of materials and components from one workstation to the next. This linear progression minimizes the distance that materials need to travel, reducing handling time and increasing overall efficiency.
- **Simplified Logistics:** With all stations aligned in a single line, the logistics of moving materials and components are simplified. It is easier to track the progress of the product as it moves through each stage of assembly.
- **Clear Visibility:** The straight-line arrangement provides clear visibility across the entire production process. Supervisors and managers can easily oversee the workflow and identify any bottlenecks or issues that arise.
- **Scalability:** An I-line layout is highly scalable. Additional workstations can be added along the line as production needs increase, allowing for easy expansion of the production capacity.
- **Flexibility in Automation:** The linear nature of the I-line makes it well-suited for automation. Automated Guided Vehicles (AGVs) or conveyor belts can be used to move materials and products along the line, further enhancing efficiency and reducing manual labor.
- **Standardization:** This layout supports standardization of processes and workstations. Each station can be designed to perform a specific task with standardized tools and procedures, ensuring consistency and quality in the final product.
- **Ergonomics:** The linear arrangement allows for ergonomic design of workstations. Operators can be positioned at appropriate intervals to minimize physical strain and optimize productivity.
- **Challenges:**
  - **Limited Flexibility:** While the I-line is efficient, it can be less flexible compared to other layouts. Changes in product design or production processes may require significant reconfiguration of the line.
  - **Space Requirements:** A straight-line layout requires a long, narrow space, which might not be feasible in all production environments.
  - **Bottleneck Risk:** If one workstation in the line experiences a delay or malfunction, it can create a bottleneck that impacts the entire production process. Effective management and maintenance are crucial to mitigate this risk.

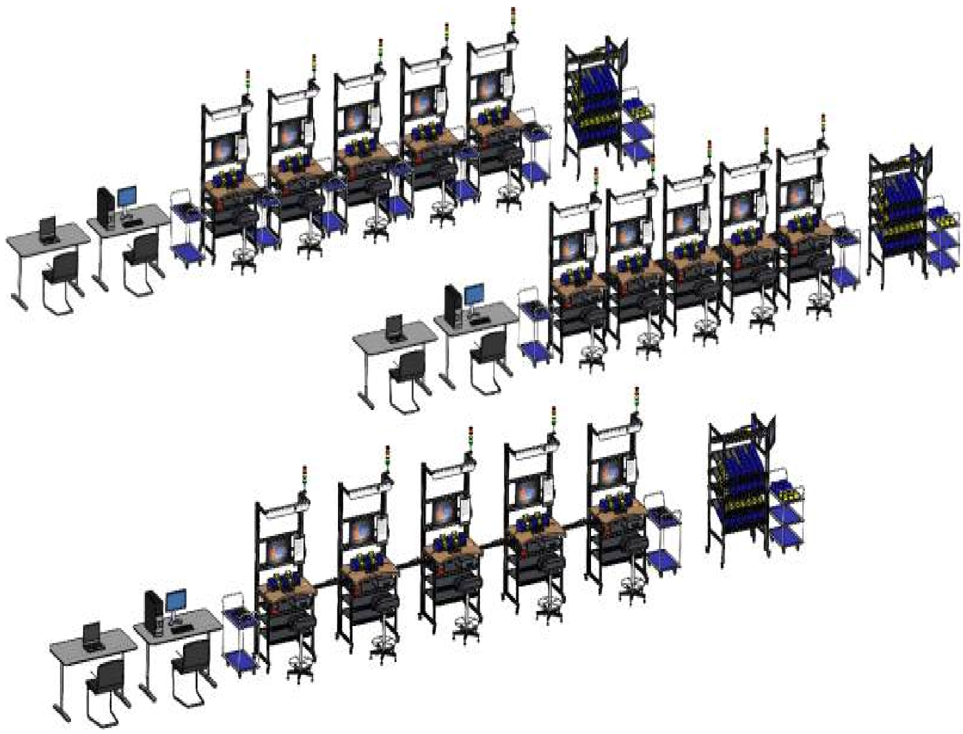

Figure II.12: Variants of Linear Implementations in Production Systems

II.2.5.6 Implementation in U-Shape

The U-shaped design strategically organizes the workspace to boost productivity and make the most of available space during manufacturing. This setup enables a smooth workflow, making it simple for workers to transition between the beginning and end of the production chain. Additionally, this arrangement often enhances communication and teamwork among employees. The U-shaped layout presents various benefits and factors to consider:

- **Enhanced Communication and Collaboration:** The U-shaped layout brings employees closer, enabling more open communication and teamwork. Co-workers can readily observe and engage with one another, leading to faster issue resolution and coordination. II.13 refers to the different U-shaped implementations possible using trolleys and conveyors.

- **Improved Space Utilization:** By arranging the workstations in a U-shape, the layout makes efficient use of available floor space. This configuration often requires less floor area compared to straight-line layouts, making it suitable for smaller production environments.

- **Efficient Workflow:** The U-shaped layout allows for a continuous and seamless flow of materials and components. The end point of the production line is close to the starting point, reducing the time and effort needed to move materials back to the beginning of the process.

- **Flexibility and Scalability:** This layout is flexible and can be easily adapted to accommodate changes in production volume or product design. Additional workstations can be added to the U-shaped line to scale up production as needed.
- **Reduced Material Handling:** The proximity of workstations in a U-shaped layout minimizes the distance that materials and components need to travel. This reduces material handling time and the risk of damage or loss during transit.
- **Ergonomics:** The U-shaped layout can be designed to optimize ergonomic conditions for workers. Workstations can be arranged to minimize physical strain and maximize productivity, contributing to a safer and more comfortable work environment.
- **Versatility in Production:** This layout supports both manual and automated processes. Automated Guided Vehicles (AGVs) or conveyor systems can be integrated into the U-shaped line to enhance efficiency and reduce manual labor.
- **Challenges:**
  - **Complex Layout Design:** Designing a U-shaped layout can be more complex compared to a straight-line layout. It requires careful planning to ensure that all workstations are easily accessible and that the workflow is smooth.
  - **Potential Congestion:** With workers and materials moving within a more confined space, there is a potential risk of congestion. Proper management and organization are essential to avoid bottlenecks and ensure a smooth flow of production.
  - **Initial Setup Costs:** The initial setup costs for a U-shaped layout can be higher due to the need for specialized equipment and layout planning. However, these costs are often offset by the long-term benefits of improved efficiency and productivity.

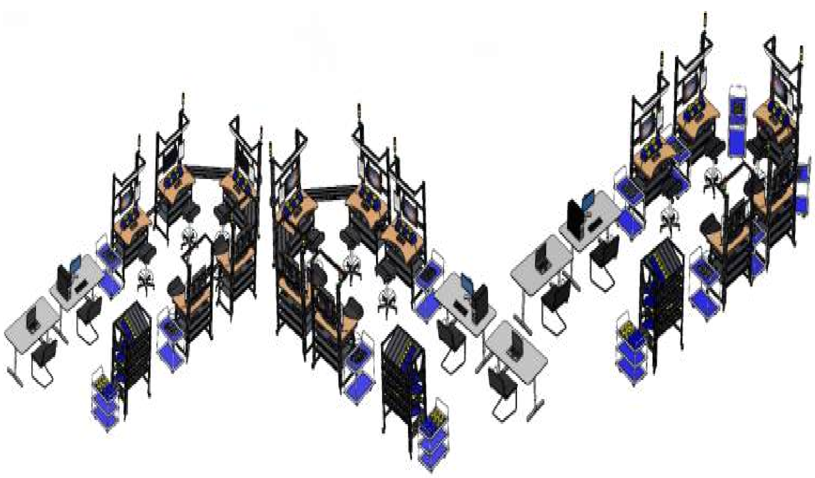

Figure II.13: Variants of U-shaped Implementations in Production Systems

II.2.6 Tulip Software in the Learning Factory

Tulip software serves as the cornerstone across all stations within the learning factory setup. This MES and Operator Assistance solution integrates seamlessly into various workflows, enhancing operational efficiency and flexibility. It facilitates visual work instructions, replacing traditional paper-based procedures with interactive and visually guided instructions. This approach simplifies operator training and supports continuous improvement of procedures.II.14

Key Use Cases

- **Visual Work Instructions:** Guides operators through visual procedures rather than paper-based instructions.
- **Training:** implifying and continuously improving training procedures through digital tools enhances learning effectiveness and operational agility in industrial environments.
- **Audit & Quality:** Replacing paper forms with IoT-enabled applications (cameras, scales, etc.) enhances quality control processes, fostering accuracy and efficiency in data collection and analysis.
- **Machine Monitoring and Maintenance:** Real-time acquisition of machine data during production ensures timely insights for optimizing operational efficiency and performance monitoring.
- **Task Tracking and Visibility:** Imports Work Orders from ERP systems (e.g., Odoo), programs production indicators (OEE, MTBF, Productivity Rate), and displays them on dashboards.
- **Digital Lean:** Embracing Digital Lean harnesses cutting-edge technologies and personalized performance dashboards to elevate productivity and transparency across manufacturing operations. By seamlessly capturing real-time data and integrating smart devices, it streamlines workflows and empowers ongoing optimization, aligning with lean principles.

Strengths

- Elimination of paper-based documents entirely.
- Easy and rapid application development with a straightforward learning curve.
- Ability to perform mathematical calculations for determining production metrics.
- Visualization of all production-related data on tablets or computers.
- Customization of dashboards by machine, production line, or product.
- Remote communication with machines through the Kepware communication server.
- Ability to use connected devices with workstations (scales, calipers, cameras, etc.).

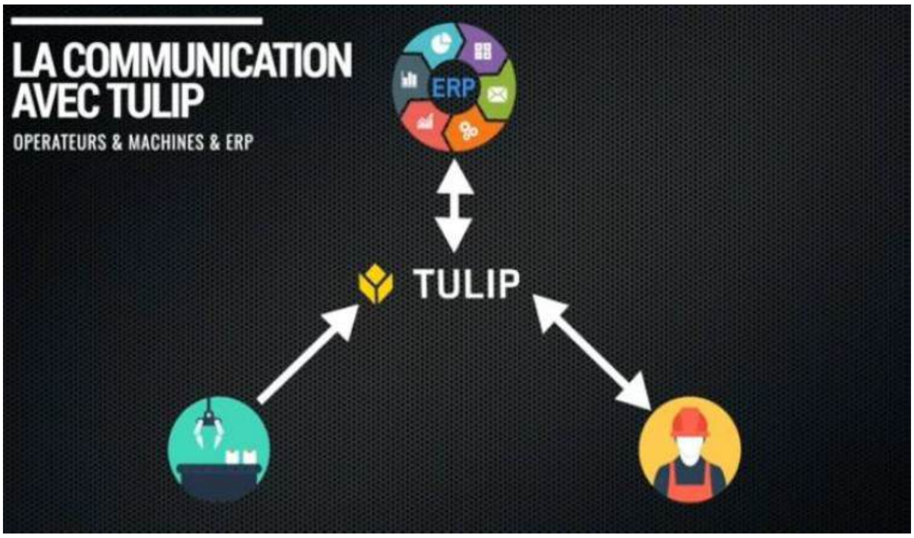

Figure II.14: Tulip software

Conclusion

learning factories have become indispensable educational hubs, transforming the way we prepare the next generation of manufacturing professionals. By blending theoretical instruction with hands-on practical experience, these specialized environments empower students to develop a comprehensive understanding of modern manufacturing processes, equipping them with the necessary tools and mindset to drive innovation and excellence in the industry.

Chapter III

Toward digital twins: simulation off-line

III.1 Introduction

The evolution of manufacturing has embraced digital twins as a transformative technology, promising to revolutionize how systems are monitored, analyzed, and optimized. Digital twins represent virtual replicas of physical assets, processes, and systems, enabling real-time simulations and analysis. This technology has the potential to revolutionize the way manufacturing processes are designed, tested, and optimized, leading to increased efficiency, reduced costs, and improved product quality.

In this chapter, we embark on the exploration of digital twins within a learning factory context, specifically focusing on offline simulation using FlexSim. Learning factories are advanced manufacturing environments that integrate production systems, automation, and information technology to provide a realistic, hands-on learning experience for students, researchers, and industry professionals. By leveraging digital twins in a learning factory setting, we can create a virtual representation of the physical environment, allowing for experimentation, testing, and optimization without disrupting the actual production operations.

Despite initial challenges in the timely implementation of a physical learning factory, we leverage offline simulations to comprehend system dynamics, we have created a digital model as a beginning to main project which is the digital twins of the Learning factory explored in the chapterII, optimize processes, and establish foundational frameworks for future real-time applications. Offline simulations enable us to explore various scenarios, test new production techniques, and make informed decisions before implementing changes in the physical learning factory. This approach not only allows for a deeper understanding of the system's behavior but also helps to mitigate risks and ensure the effectiveness of any proposed improvements.

By utilizing digital twins in a learning factory context, we can create a tested for innovative manufacturing solutions. This virtual environment provides a safe and controlled setting for experimenting with new technologies, processes, and control strategies, without the need for costly physical infrastructure or the risk of disrupting ongoing production. The insights gained from these offline simulations can then be used to inform the design and implementation of the physical learning factory, ensuring that it is optimized for maximum efficiency and effectiveness.

Furthermore, the use of digital twins in a learning factory setting can serve as a valuable educational tool. Students and researchers can explore the intricacies of manufacturing processes, experiment with different scenarios, and gain hands-on experience in a risk-free environment. This approach not only enhances their understanding of manufacturing systems but also prepares them for the challenges they may face in the real-world industrial setting.

In this chapter,

III.2 Problem statement

Our investigation utilizes FlexSim, an advanced simulation software, to replicate a sophisticated manufacturing environment consisting of five crucial stations. Four of these stations are dedicated to production tasks, each performing identical functions, while the fifth station acts as a quality control checkpoint to ensure the integrity of the final product.

Initially, our model is a flowshop manufacturing system, and it can take multiple forms (Job shop, flexible flowshop...). Operated without human operators, allowing us to establish baseline performance metrics for the automated system. This approach provided a foundational understanding of the facility's capabilities and limitations in a hands-off operational mode.

Recognizing the pivotal role of human involvement in real-world manufacturing scenarios, we extended our simulation to incorporate human operators. This enhancement enables us to simulate realistic operational dynamics, where skilled workers collaborate with automated systems to enhance overall efficiency and productivity.

Our study is designed to execute and compare two distinct sets of production scenarios across these models. By analyzing the efficiencies and operational impacts of both automated and human-integrated systems, we aim to derive valuable insights that inform decision-making and optimization strategies for the manufacturing environment.

The integration of FlexSim's advanced simulation capabilities, coupled with the strategic inclusion of human operators, allows us to meticulously explore the intricate interplay between automation and human intervention. This multifaceted approach promises to yield a deeper understanding of the manufacturing system's performance dynamics and unlock opportunities for continuous improvement.

III.3 FlexSim Models

As discussed in Chapter I, FlexSim stands out as a powerful simulation software renowned for its capability to model diverse scenarios and visualize various aspects of complex systems. Beyond simulation, FlexSim offers robust tools for creating customized dashboards and conducting comparative analyses between different scenarios.

In this section, we will explore the application of FlexSim in our study, focusing on two distinct models: one emphasizing automated stations and another centered on human-centric operations.

FlexSim enables us to construct detailed simulations that accurately replicate real-world manufacturing environments. The first model simulates an automated setup where manufacturing processes across four dedicated stations and a quality control checkpoint operate without human intervention. This model allows us to establish baseline performance metrics and understand the efficiency of fully automated operations.

In contrast, the second model integrates human operators into the simulation, reflecting real-world manufacturing scenarios where skilled workers interact with automated systems. This human-centric model explores how human intervention influences production efficiency, quality control, and overall system dynamics.

Throughout our investigation, we leverage FlexSim's advanced features to compare and analyze these two models comprehensively. We utilize FlexSim's dashboarding capabilities to visualize key performance indicators and monitor system behavior in real-time. Comparative analysis between the automated and human-centric models will provide insights into the advantages and trade-offs associated with each operational approach.

By harnessing FlexSim's simulation prowess, our study aims to deepen understanding of manufacturing processes, optimize operational strategies, and inform decision-making for enhancing productivity and quality in industrial settings.

III.4 Off -line simulation models

III.4.1 Model A: Without Human work forces

Model A as shown in figure III.1 before simulation and figure III.2 after the simulation. It represents the initial simulation configuration devoid of human factors. This model aims to establish baseline performance metrics and evaluate the efficiency of the manufacturing system under ideal conditions. Production scenarios in ranges A is simulated to analyze throughput, bottlenecks, and resource utilization without the variability introduced by human operators.

III.4.2 Key Performance Indicators (KPIs) Definition

Key Performance Indicators (KPIs) serve as pivotal metrics for evaluating the efficacy and performance of our digital twin simulation model. These KPIs include:

- **State of Each Buffer:** Assessment of the status and utilization levels of buffers within the production system, crucial for understanding material flow and congestion.
- **Work-in-Process (WIP):** Quantification of work-in-process inventory at different stages of the manufacturing process, indicative of production efficiency and throughput.
- **Stay Time in Each Machine and Buffer:** Measurement of the duration components spend at each machine and buffer, offering insights into process bottlenecks and resource utilization.
- **Utilization Rate:** Calculation of machine utilization rates, highlighting the efficiency of resource allocation and identifying underutilized or overburdened assets.

- **Output of each station:** output of each station summarize for us the results , such as the bottleneck station , which operator we should eliminate ...

These KPIs are instrumental in providing a comprehensive assessment of the digital twin model's performance, facilitating informed decision-making and continuous improvement strategies within the manufacturing environment.

System Parameters

The following table summarizes the key parameters and characteristics of the manufacturing system under study:

Parameter	**Value**
Input (Raw Material) Distribution	Exponentially distributed, mean of 25 seconds
Maximum Content of Buffers	10
Station 1 Process Time	2 minutes
Station 2 Process Time	1 minute
Station 3 Process Time	3 minutes
Station 4 Process Time	3 minutes
Station 5 (Quality Control) Process Time	1 minute

Table III.1: System Parameters

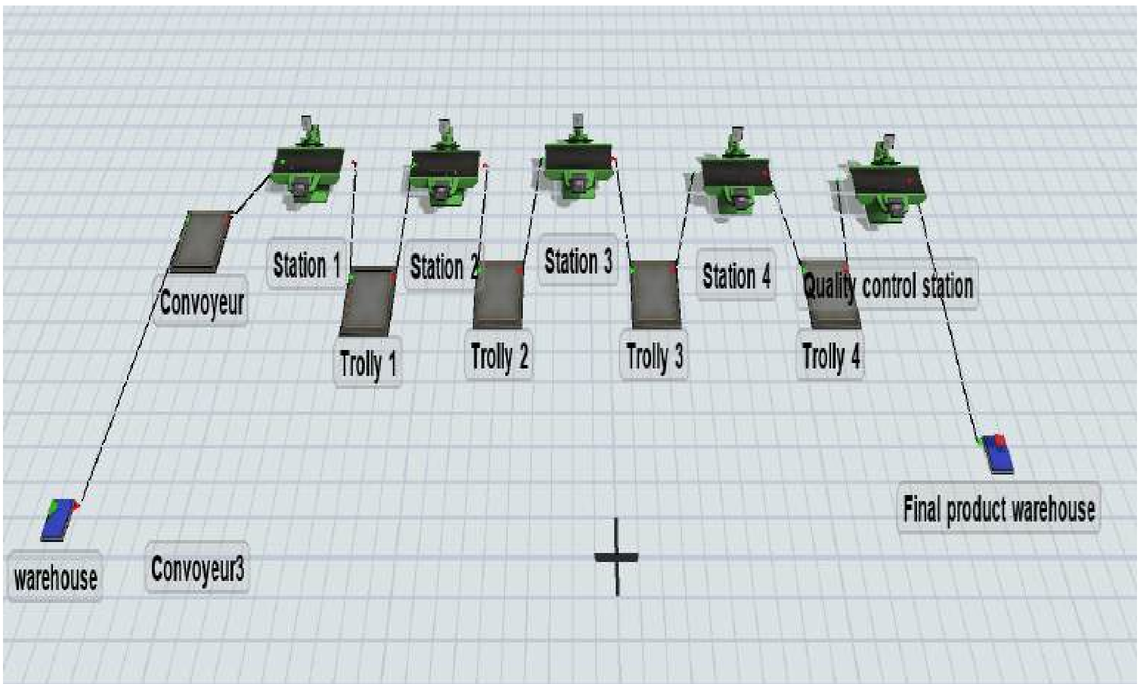

Figure III.1: Before the simulation of the range A

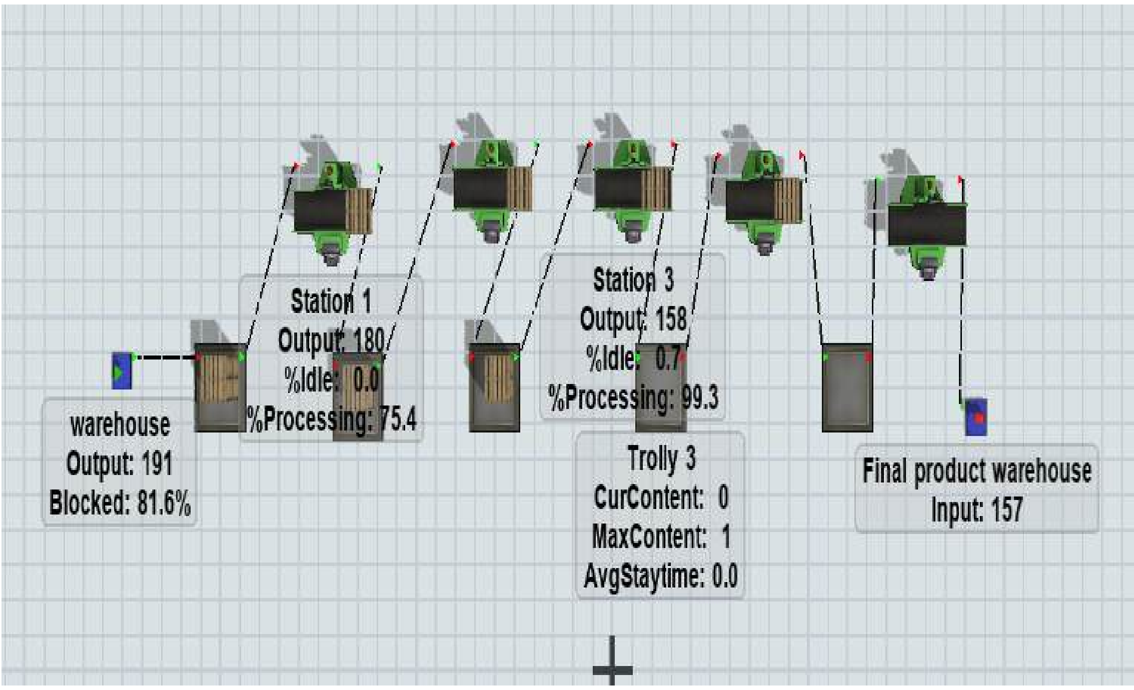

Figure III.2: After the simulation of the range A

Results

the results of the Model A without considering human factors showed us the following

Wip of each instance in the model

Object	WIP
stock1	10
Trolly 1	10
Trolly 2	10
Trolly 3	0
Trolly 4	0

Figure III.3: WIP in each buffer

taytime in each instance in the mode

Object	AvgStaytime	MinStaytime	MaxStaytime
stock1	1525.15	0	1800
Trolly 1	1297.06	0	1800
Trolly 2	1624.53	0	1800
Trolly 3	0.00	0	0
Trolly 4	0.00	0	0

Figure III.4: Staytime in each buffer

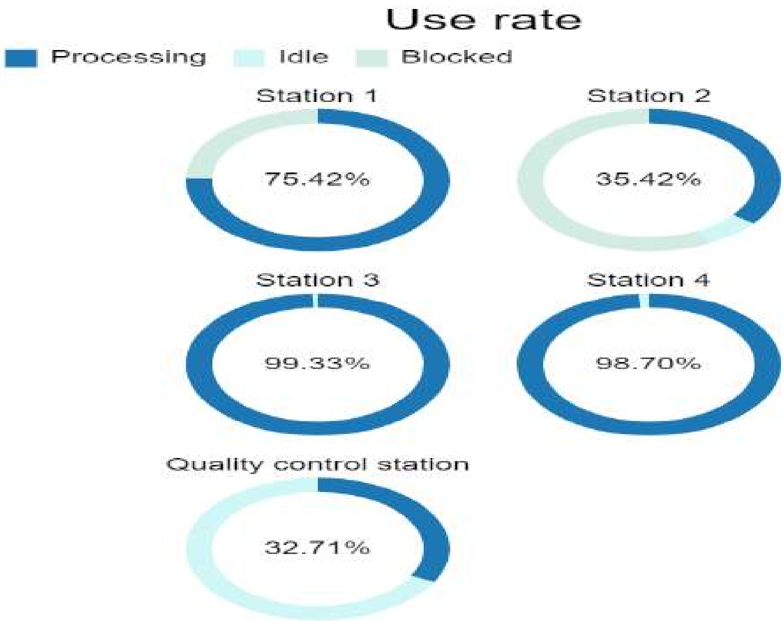

Figure III.5: Use rate of each station

Output

Object	Throughput
Station 1	180
Station 2	169
Station 3	158
Station 4	157
Quality control station	157

Figure III.6: Output of each station

Model A : Results Discussion

In Model A in the offline simulation, As show in figure III.6 the station number 4 and 5 emerged as the bottleneck within the manufacturing process. This bottleneck indicates that station 4 and 5 had the lowest output relative to its capacity, potentially causing delays and limiting the overall throughput of the production line. Bottlenecks are critical points where production capacity is constrained, often requiring optimization strategies to alleviate congestion and improve flow efficiency.

Additionally, as we can see in figure III.3 buffer trolley 1,2 and stock 1 exhibited the highest Work-in-Progress (WIP) compared to other buffers in range A. High WIP in buffer trolley 1 suggests that materials accumulated at this point, potentially due to delays upstream (before station 2) or inefficiencies in downstream processes. Managing WIP levels is crucial to maintaining smooth production flow, as excessive inventory can lead to increased lead times, storage costs, and potential quality issues.

Stations 3 and 4 in our manufacturing setup are operating at utilization rates exceeding 98%, indicating they are consistently near maximum capacity and play a crucial role in our production process. These high utilization rates underscore the necessity for robust preventive maintenance strategies. Preventive maintenance involves scheduled inspections, repairs, and upkeep aimed at minimizing downtime and extending equipment lifespan. Given the intensive use of Stations 3 and 4 as was demonstrated in III.5, they are more susceptible to accelerated wear and potential breakdowns if not adequately maintained.

To effectively manage these critical assets, our preventive maintenance plan includes regular inspections to detect and address potential issues early. Routine maintenance tasks such as lubrication, calibration, and cleaning are essential to ensuring optimal performance and reliability. Additionally, implementing predictive maintenance techniques, such as condition monitoring and sensor-based analytics, allows us to anticipate maintenance needs based on real-time operational data.

Prioritizing preventive maintenance for Stations 3 and 4 not only reduces the risk of unplanned downtime but also supports consistent production output and extends the operational lifespan of these vital components. By proactively maintaining these high-utilization stations, we enhance overall operational efficiency and minimize disruptions in our manufacturing processes.

Addressing these observations involves strategic adjustments in scheduling, resource allocation, or process redesign. By mitigating bottlenecks at station 4 and 5 through improved resource utilization or workflow optimization, and managing WIP levels in buffer trolley 1,2 and the stock 1 through synchronized production planning, the manufacturing system can enhance throughput, reduce cycle times, and ultimately improve overall operational efficiency.

These insights from range A provide valuable data for refining the simulation model, optimizing production strategies, and achieving smoother operations in subsequent simulation ranges and real-world implementations.

III.5 Model B: Integration of Human Operators

Model B extends the simulation to incorporate human operators, aiming to replicate real-world manufacturing environments more accurately. In this model, one operator serves as a transporter between Stock 1 and Station 1, enhancing operational realism by simulating human intervention in material handling. This operator has a capacity of 1 and follows specific load and reload times, ensuring efficient material flow between the stock and station.

Additionally, the simulation as shown in figure **??** includes five operators assigned to their respective stations. These operators are integral to their stations' operations, handling tasks such as job transportation as we can see in the figure **??** and equipment setup. When a job is completed at a station, the respective operator must transport it to the next buffer. This setup introduces variability in task completion times and decision-making dynamics, reflecting the complexities of human involvement in manufacturing processes.

Furthermore, the integration of human factors in Model B provides insights into how operator availability impacts production flow. If a job arrives at a station while its designated operator is engaged elsewhere, it must wait until the operator becomes available to transport it to the next buffer. This aspect simulates realistic scenarios where operational efficiency is influenced by workforce dynamics and task prioritization.

By incorporating these human factors, Model B not only enhances the simulation's accuracy but also allows for a deeper analysis of operational challenges and opportunities for optimizing production efficiency and resource utilization.

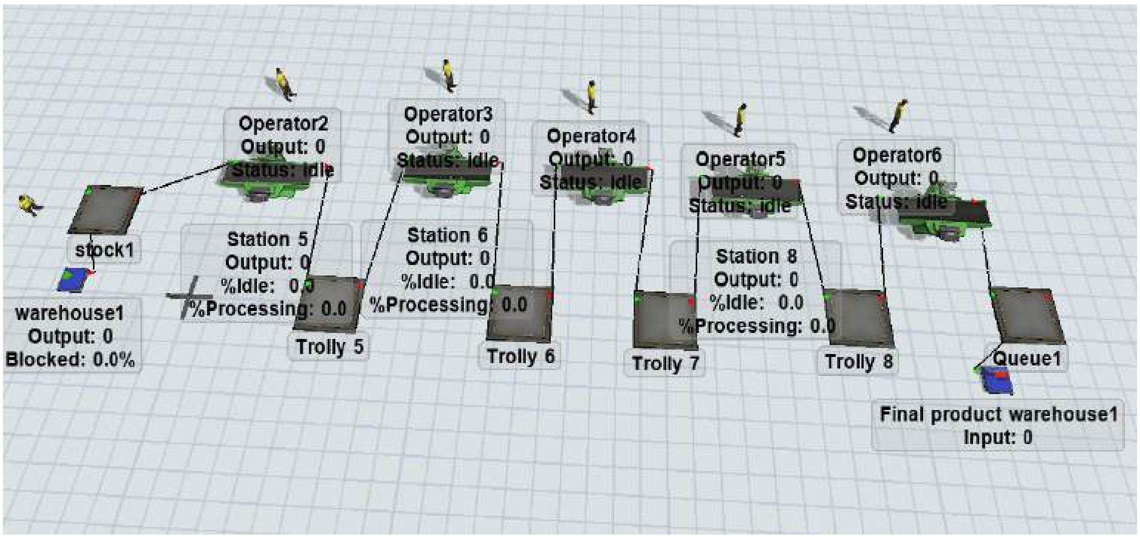

Figure III.7: Simulation model B before running the model

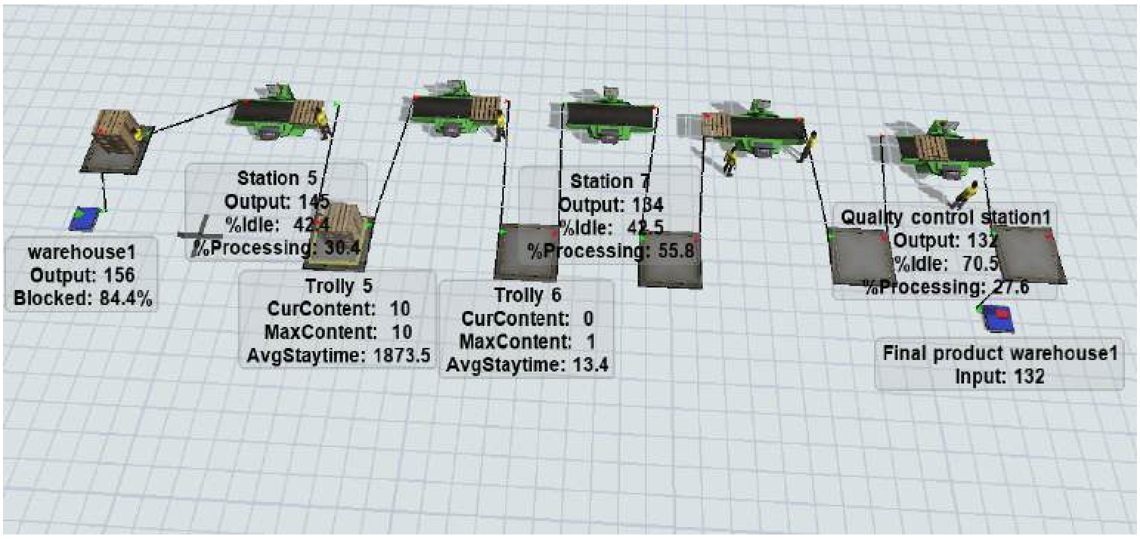

Figure III.8: Simulation model B before running the model

Results

the results of the Model B with considering human factors showed us the following

Content

Object	WIP
stock1	10
Trolly 5	0
Trolly 6	3
Trolly 7	0
Trolly 8	0

Figure III.9: WIP in each buffer

Staytime

Object	AvgStaytime	MinStaytime	MaxStaytime
stock1	1979.97	42.40	2077.45
Trolly 5	13.23	13.21	14.89
Trolly 6	242.51	15.16	495.19
Trolly 7	13.69	13.17	14.95
Trolly 8	13.04	13.02	14.86

Figure III.10: Staytime in each buffer

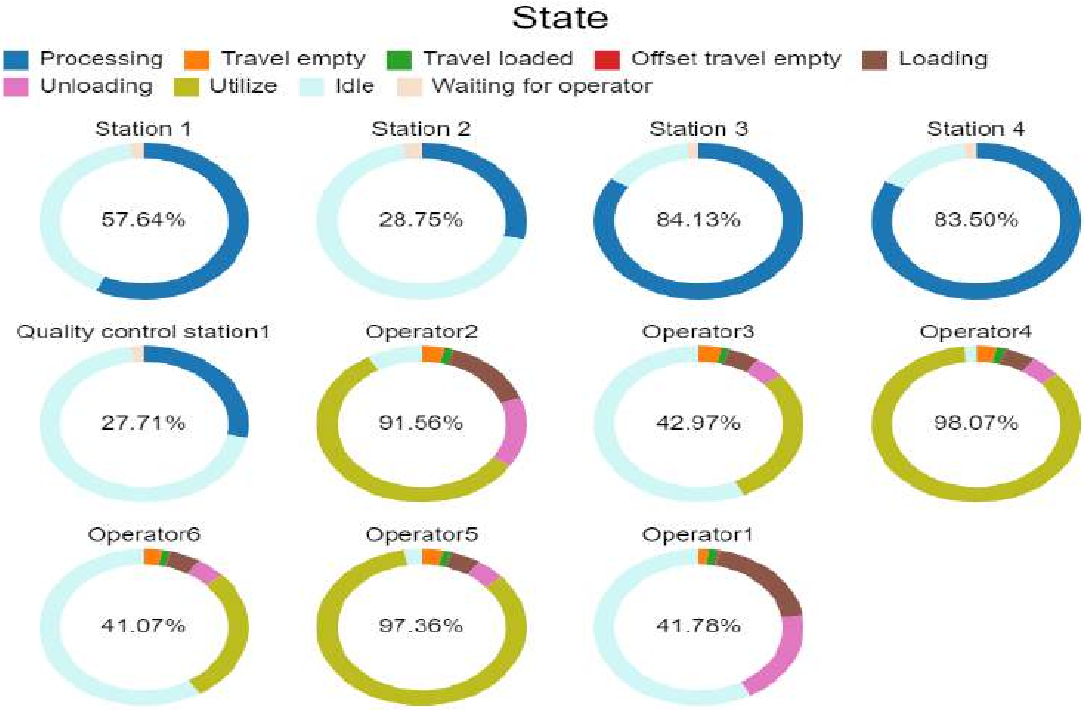

Figure III.11: Use rate of each station

Output

Object	Throughput
Station 1	138
Station 2	137
Station 3	134
Station 4	133
Quality control station1	133

Figure III.12: Output of each station

Model B: Incorporation of Human Operators

In Model B, as shown in Figure III.7 before the simulation and in figure III.8, the introduction of human operators has been incorporated to reflect real-world manufacturing environments more accurately. The utilization rates of Stations 3 and 4 were notably high, exceeding 98%, due to their longer processing times relative to other stations. This heightened utilization underscores the necessity for targeted preventive maintenance strategies to prevent breakdowns and maintain efficiency.

Furthermore, the Work-in-Progress (WIP) levels were observed to peak at Stock 1, as illustrated in Figure III.9. This can be attributed to the exponential distribution of input materials (mean of 25 seconds), coupled with the additional time required by operators to select and unload raw materials. These factors contributed to significant material accumulation at Stock 1, highlighting the need for improved material handling and operator efficiency.

The output Key Performance Indicators (KPIs) III.12 provided insights into bottlenecks within the system, identifying the Quality Control station and Station 4 as critical points of congestion. To address this, several optimization strategies can be implemented. One approach is to distribute quality control tasks along the production line, ensuring continuous inspection and reducing the load on a single quality control station. Additionally, adding a parallel station alongside Station 4 can enhance its throughput capacity, alleviating the bottleneck and improving overall system efficiency.

Preventive maintenance remains crucial for high-utilization stations like 3 and 4 , wa can clearly see that form the figure III.11. Scheduled inspections and cleaning are essential to ensure these stations operate reliably. Implementing predictive maintenance techniques, such as condition monitoring and sensor-based analytics, allows for early detection of potential issues, further minimizing downtime and extending equipment lifespan.

Incorporating human operators also revealed high utilization rates for operators, particularly operators 2, 4, and 5. This high usage rate indicates that these operators are consistently engaged, leading to potential fatigue and increased risk of accidents. To mitigate these risks, it is essential to introduce breaks once the utilization rate surpasses a certain threshold. The learning factory environment is ideal for implementing and testing these safety measures, as it provides a controlled and safe setting to monitor operator performance and adjust schedules accordingly.

Addressing these observations involves strategic adjustments in scheduling, resource allocation, and process redesign. By mitigating bottlenecks at the Quality Control station and Station 4 through improved resource utilization and workflow optimization, and managing WIP levels at Stock 1 through synchronized production planning, the manufacturing system can enhance throughput, reduce cycle times, and ultimately improve overall operational efficiency.

These insights from Model B provide valuable data for refining the simulation model, optimizing production strategies, and achieving smoother operations in subsequent simulation ranges and real-world implementations.

Comparison with Model A

When comparing the results of Model B with Model A, several key differences emerge. In Model A, the Work-in-Progress (WIP) levels were generally higher throughout the system, except for Stock 1. This difference can be attributed to the role of operators in Model B, who actively manage and transport products between stations, reducing WIP levels in other buffers. In Model A, the automated system lacks this dynamic interaction, leading to higher WIP levels.

The utilization rates in Model B for operators, especially operators 2, 4, and 5, were significantly higher than in Model A. This is due to the operators' responsibilities of not only completing tasks but also transporting products to the next station. This additional duty reduces their availability and increases their utilization rates.

However, the overall output was higher in Model A, the fully automated mode. This is a logical result, as automated systems typically exhibit greater efficiency and consistency, albeit with less flexibility. In contrast, Model B, with its integration of human operators, reflects the need for balancing efficiency with adaptability and human oversight.

In conclusion, the automated system in Model A demonstrates high efficiency with less flexibility, while Model B provides a more realistic depiction of human-machine collaboration, emphasizing the need for strategic operator management and preventive maintenance to optimize performance.

Conclusion

The insights derived from Model B underscore the significant advantages of digital modeling in modern manufacturing systems. Digital modeling allows for detailed analysis and optimization of both automated and human-centric processes, providing a comprehensive understanding of system dynamics without disrupting physical operations.

The incorporation of human operators is essential in domains where their intelligence, decision-making capabilities, and adaptability are irreplaceable. However, this integration also necessitates strategies to manage operator workload effectively. High utilization rates observed in certain operators highlight the need for scheduled breaks to prevent fatigue and accidents, emphasizing the importance of maintaining operator well-being.

The learning factory environment plays a crucial role in this context, offering a controlled and safe setting to experiment with and refine such strategies. By leveraging digital modeling, we can simulate various scenarios and develop optimized solutions. For operations requiring significant workforce involvement, we can utilize automation to handle repetitive or labor-intensive tasks, thereby improving overall efficiency and reducing the strain on human operators.

The combination of digital modeling and strategic human-automation integration provides a powerful approach to enhancing manufacturing systems. By implementing solutions such as operator breaks and targeted automation, we can achieve a balanced and efficient production process that leverages the strengths of both human intelligence and automated systems.

Conclusion

III.6 Conclusion

In conclusion, the development and implementation of a digital model in manufacturing systems has provided a transformative approach to optimizing production processes and enhancing overall efficiency. This project has successfully elaborated a digital model and simulated various scenarios to compare automated and human-centric modes. The results from these simulations provide valuable insights into the dynamics of production systems, highlighting the critical role of human operators and the potential efficiencies of fully automated systems.

The digital model enabled a detailed analysis of key performance indicators (KPIs) such as work-in-progress (WIP), stay time in buffers, and station utilization rates. By comparing these metrics between the automated and human-centric models, we identified areas for improvement and potential bottlenecks in the production process. The human-centric model revealed the impact of operator availability on job arrival wait times, emphasizing the need for effective human resource management in manufacturing environments.

Looking ahead, there are several exciting perspectives for expanding this research. One promising direction is the elaboration of digital twins for the learning factory. This would provide a hands-on, interactive environment for students and professionals to engage with digital twin technology, fostering a deeper understanding of its applications and benefits in real-world manufacturing settings.

Another critical area for future research is incorporating fatigue and recovery parameters into the digital model. Human operators play a vital role in many manufacturing systems, and their performance can significantly impact overall efficiency. By simulating fatigue and recovery, we can develop more realistic models that account for human factors, leading to better workforce management and improved productivity.

Additionally, the concept of a digital shadow offers a compelling next step in this ambitious project. A digital shadow, which provides real-time data and analytics, can further enhance the digital model by offering continuous monitoring and feedback. This would enable more dynamic and responsive adjustments to the manufacturing process, ensuring optimal performance and reducing downtime.

Overall, the successful implementation of the digital model in this project marks a significant milestone in the journey towards smarter, more efficient manufacturing systems. By continuing to explore these innovative perspectives, we can unlock new levels of productivity, sustainability, and adaptability in the manufacturing industry.

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