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Grado en Ingeniería Electrónica Industrial y Automática

Automatización industrial aplicada a un proceso de logística interna

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Resumen

Este trabajo presenta el desarrollo de un sistema de automatización industrial para gestionar la reposición de piezas desde el almacén hasta los puestos de trabajo en un entorno de fabricación. Basado en la metodología Kanban, el sistema se implementa en la Lean Room del Factory Lab de la Universidad de Coímbra.

El proyecto incluye el análisis del problema, la definición de objetivos, la revisión de soluciones comerciales, la selección de hardware, el desarrollo de software, el modelado 3D, las pruebas funcionales y la instalación final. El núcleo del trabajo es un sistema electrónico Kanban (E-Kanban) flexible y escalable, capaz de aplicar estrategias de *kitting* y *line stocking*.

La integración de robots móviles automatiza el transporte de piezas, mejora la precisión, reduce la manipulación manual y asegura la continuidad de la producción. Con ello, el sistema refuerza los principios *lean*, aumenta la eficiencia y sienta bases para la fabricación inteligente.

Keywords: E-Kanban, Lean Manufacturing, Robots Móviles, Sistemas Pick to Light, Automatización Industrial.

Abstract

This work presents the development and deployment of a multidisciplinary industrial automation system for managing parts replenishment from the warehouse to workstations in a manufacturing environment. Based on the Japanese Kanban method, the system is implemented in the Lean Room of the Factory Lab at the University of Coimbra.

The project includes problem analysis, objective definition, market research, hardware selection, software development, 3D modeling, functional testing, and final installation. The main goal is a flexible and scalable electronic Kanban (E-Kanban) system capable of handling two strategies: *kitting* and *line stocking*, automatically signaling required parts and workstations.

The system is enhanced by integrating mobile robots, automating transport, reducing manual handling, increasing speed, and ensuring accuracy. This improves real-time responsiveness, minimizes human error, and supports continuous production. Aligning with lean principles, the system reduces waste, shortens cycle times, and enhances resource utilization, providing a foundation for future smart manufacturing automation.

Keywords: E-Kanban, Lean Manufacturing, Mobile Robots, Pick to Light, Industrial Automation.



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Rodrigo Melchor Gómez

INDUSTRIAL AUTOMATION APPLIED TO AN INTERNAL LOGISTICS PROCESS

**Dissertation within the scope of the Master's degree in Industrial and
Management Engineering supervised by Doctor Jérôme Mendes and Professor
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Abstract

This work presents the development and deployment of a multidisciplinary industrial automation system designed to manage the replenishment of parts from the warehouse to workstations in a manufacturing environment. The system follows a parts replenishment methodology based on the Japanese Kanban method and is implemented in the Lean Room of the Factory Lab at the University of Coimbra.

The project involves the study and analysis of the replenishment problem, the definition of objectives, market research on existing commercial solutions, hardware selection, software development, 3D modeling, functional testing, and final installation. The core goal is to implement a flexible and scalable electronic Kanban (E-Kanban) system capable of handling two replenishment strategies: kitting and line stocking. The system automatically signals which parts are needed and to which workstation, improving the reliability and responsiveness of material flow within the production line.

As part of this work, the system was significantly enhanced by integrating mobile robots into the replenishment process. These robots automate the transportation of parts from the warehouse to the workstations, reducing manual handling, increasing speed, and ensuring accuracy in deliveries. This integration strengthens the system's real-time responsiveness, minimizes human error, and supports continuous production with minimal interruptions.

The implementation of mobile robotics has also improved adaptability to dynamic demand, enabling autonomous, precise, and efficient deliveries based on workstation requests. The system aligns with lean manufacturing principles by reducing waste, shortening cycle times, and improving resource utilization. Overall, the enhanced E-Kanban system has contributed to greater production efficiency and lays a strong foundation for future automation innovations in smart manufacturing.

Keywords: E-Kanban, Lean Manufacturing, Mobile Robots, Pick to Light, Industrial Automation, Parts Replenishment.

Resumo

Este trabalho apresenta o desenvolvimento e a implementação de um sistema multidisciplinar de automação industrial, concebido para gerir o reabastecimento de peças desde o armazém até os postos de trabalho num ambiente de produção. O sistema segue uma metodologia de reabastecimento baseada no método japonês Kanban e foi implementado na Lean Room do Factory Lab da Universidade de Coimbra.

O projeto inclui o estudo do problema, a definição de objetivos, a análise de soluções comerciais existentes, a seleção de hardware, o desenvolvimento de software, a modelação 3D, testes funcionais e a instalação final. O principal objetivo é implementar um sistema eletrónico de Kanban (E-Kanban) flexível e escalável, capaz de gerir dois métodos de reabastecimento: kitting e line stocking. O sistema sinaliza automaticamente quais peças são necessárias e em qual posto de trabalho, melhorando a fiabilidade e a agilidade do fluxo de materiais na linha de produção.

Como parte deste trabalho, o sistema foi significativamente melhorado com a integração de robôs móveis no processo de reabastecimento. Estes robôs automatizam o transporte das peças do armazém para os postos de trabalho, reduzindo a necessidade de manipulação manual, aumentando a velocidade e garantindo a precisão nas entregas. Esta integração reforça a capacidade de resposta em tempo real do sistema, minimiza erros humanos e assegura uma produção contínua com mínimas interrupções.

A utilização de robótica móvel também aumentou a adaptabilidade do sistema à procura dinâmica, permitindo entregas autónomas, precisas e eficientes com base nas solicitações dos postos de trabalho. O sistema está alinhado com os princípios da manufatura lean, ao reduzir desperdícios, encurtar tempos de ciclo e melhorar a utilização dos recursos. No geral, o sistema E-Kanban melhorado contribuiu para uma maior eficiência produtiva e estabelece uma base sólida para futuras inovações em automação na indústria 4.0.

Palavras-chave: E-Kanban, Lean Manufacturing, Robôs móveis, Pick to Light, Automação industrial, Reposição de peças .

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Acronyms

AGV Automated Guided Vehicle.

AMR Autonomous Mobile Robot.

API Application Programming Interface.

E-Kanban Electronic Kanban.

ERP Enterprise Resource Planning.

FDM Fused Deposition Modeling.

FIFO First In, First Out.

FL Factory Lab.

GPIO General Purpose Input/Output.

GUI Graphical User Interface.

IP Internet Protocol.

JIT Just-In-Time.

JSON JavaScript Object Notation.

LED Light Emitting Diode.

LiDAR Laser Imaging Detection and Ranging.

MES Manufacturing Execution System.

MiR Mobile Industrial Robot.

MQTT Message Queuing Telemetry Transport.

OPC UA Open Platform Communications Unified Architecture.

PLC Programmable Logic Controller.

QR Quick Response.

RAM Random Access Memory.

REST Representational State Transfer.

RFID Radio-Frequency Identification.

SLAM Simultaneous Localization and Mapping.

TPS Toyota Production System.

UI User Interface.

USB Universal Serial Bus.

Wi-Fi Wireless Fidelity.

WIP Work In Process.

WS Workstation.

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Chapter 1

Introduction

The present work is part of a broader educational and technological initiative carried out within the Factory Lab (FL), a simulated industrial environment designed to support hands-on learning and experimentation with real manufacturing technologies (see Figure 1.1). This environment replicates the key elements of a modern production cell, including workstations, storage systems, programmable controllers, barcode scanners, Light Emitting Diode (LED) signaling, and mobile robotics.

The goal of the Factory Lab is to provide a realistic but controlled space in which students and researchers can develop, test, and validate solutions inspired by modern industrial challenges (see Figure 1.2). Within this framework, this project focuses on the design and implementation of a flexible and semi-automated material handling system, where technologies such as visual interfaces, programmable logic, and mobile robots are combined to simulate real production flows based on Lean Manufacturing principles.

1.1 Relevance of the Project in Today's Industry

In the context of Industry 4.0 and the increasing demand for agile, reliable, and low-waste production systems, manufacturing companies are undergoing a deep transformation in how materials are handled, tracked, and delivered across the factory floor. Among the critical processes under scrutiny are intralogistics and workstation replenishment, which—despite often being overlooked—can generate significant inefficiencies when poorly managed.

Traditional systems that rely on manual transport, paper-based tracking, or fixed delivery schedules often suffer from excess inventory, bottlenecks, operator confusion, and even assembly errors caused by missing or wrong parts. To address these challenges, many companies are adopting digital replenishment strategies, often derived from Lean Manufacturing, including methods such as Kitting and Line Stocking.

- In **Kitting**, all the components needed for a specific assembly task are pre-collected into a kit and delivered as a single unit to the workstation. This reduces the operator's decision load, simplifies part selection, and helps prevent errors, especially in high-mix environments or when production is highly customizable.
- In contrast, **Line Stocking** involves having trays or bins with individual components available at each station. The operator selects the needed parts as they perform their tasks. This method provides higher flexibility and is particularly effective when the same components are shared across multiple products or variants.



Figure 1.1: Lean Room in Factory Lab.



Figure 1.2: Students working at Factory Lab.

Both methods are often implemented within the framework of Kanban systems, which are visual signaling mechanisms used to control inventory levels and trigger replenishment actions only when necessary. Originally developed by Toyota, Kanban encourages a pull-based logic, where production and supply respond to real consumption, thus reducing overproduction and improving flow. In modern manufacturing, these systems are increasingly digitized through E-Kanban solutions, enabling real-time data transmission and integration with Enterprise Resource Planning (ERP) or Manufacturing Execution System (MES) platforms.

By incorporating Kitting, Line Stocking, and Kanban logic into this project, the system is able to simulate real-time replenishment flows and dynamic tray handling. This creates a close approximation of how modern factories operate — combining Lean methodology, operator interaction, and digital automation.

Furthermore, the integration of Autonomous Mobile Robot (AMR) [1] and the deployment of operator interfaces and Programmable Logic Controller (PLC) mirror the current industrial shift toward decentralized, responsive, and traceable production cells. These technologies not only reduce non-value-added activities, but also contribute to error - proofing, efficiency, and continuous improvement (Kaizen) efforts.

Ultimately, the relevance of this project lies in its ability to bring together key concepts from Lean Manufacturing, digital intralogistics, and industrial automation into an accessible and functional implementation within the FL environment.

1.2 Objectives

This project was developed as a continuation and expansion of a previous implementation¹, which introduced a basic material supply system in the Factory Lab. This project represented the initial concept, but it relied on blocking loops, lacked autonomous transport capabilities, and was limited in terms of interface usability and scalability. Building upon that foundation, the current project aims to redesign and extend the system architecture, enhancing both its functional capabilities and its resemblance to real-world industrial systems.

The main objective is to implement a robust and modular logistics system, capable of adapting to different replenishment strategies, supporting autonomous transport, and offering responsive operator interaction. In order to achieve this, several lines of work were established:

- Deployment of a distributed control network;
- Development of a centralized visual interface;
- Integration of a MiR100 mobile robot for autonomous transport;
- Support for multiple replenishment strategies;
- Improvement of electrical and hardware integration;
- Optimization of control logic and system stability;
- Real-world testing and performance validation.

¹Developed by student Jorge González García in 2024.

1.3 Project Structure

This document is structured into five chapters, each focusing on a specific aspect of the project's development and implementation:

- **Chapter 1 – Introduction**

Presents the general context and motivation behind the project. It explains the relevance of intralogistics automation in today's industry and introduces the Factory Lab environment where the system has been implemented.

- **Chapter 2 – Concepts**

Provides the foundation of the project, covering Lean Manufacturing principles, Kanban systems, and material replenishment strategies such as Kitting and Line Stocking. It also includes an overview of mobile robotics in industry, with special focus on the MiR100 platform.

- **Chapter 3 – Analysis of Supply Strategies: Kitting and Line Stocking**

Focuses on the analysis of the case study, detailing the components and elements that will be used in the project implementation. It also provides an explanation of the replenishment methods applied, primarily Kitting and Line Stocking, which are fundamental to optimizing the material flow and ensuring efficient supply within the warehouse environment. These methods are described in terms of their principles, operational workflow, and relevance to the overall logistics system.

- **Chapter 4 – Implementation and testing**

Details the technical development of the system, including hardware integration, software architecture, visual interface design, and the configuration of material flow and robot missions. This chapter also explains the replenishment logic and user interaction mechanisms.

- **Chapter 5 – Conclusions and future work**

Summarizes the outcomes of the project and reflects on its contributions. It also proposes possible improvements and extensions to be explored in future iterations.

Chapter 2

Concepts

This chapter provides the theoretical framework that underpins the implementation developed in this project. It introduces the fundamental principles of Lean Manufacturing, along with the material replenishment strategies commonly used in modern production environments, particularly assembling and stocking. In addition, it explores the role of AMR in industrial logistics, focusing on how these technologies [1], are increasingly integrated into Lean systems to automate internal transport, reduce waste, and improve responsiveness. These concepts serve as the foundation for the design decisions and improvements presented in the following chapters.

2.1 Lean Management

The concept of Lean Management has its origins in the production system developed by Toyota in the second half of the 20th century, known as the Toyota Production System (TPS) [2]. This system revolutionized the industry by proposing a completely new way of managing production, with the aim of maximizing customer value while minimizing the resources employed. From this experience in the Japanese automotive industry, a broader philosophy, known as Lean, emerged, which has been progressively adopted in sectors as diverse as healthcare, software, logistics, and education. Lean Management is based on three fundamental pillars [2, 3]:

- **Value delivery:** clearly identify what the customer needs and eliminate everything that does not directly contribute to that value.
- **Elimination of waste (muda):** reduce or eliminate resources, time, movements, processes, or inventory that do not generate added value.
- **Continuous improvement (kaizen):** foster a culture of constant improvement, driven by all levels of the organization.

One of the key contributions of the Lean approach was the identification of seven types of waste (muda), including overproduction, waiting times, unnecessary transportation, excess inventory, unnecessary movements, overprocessing, and defects [2, 3]. In more current contexts, an eighth type of waste is added: the waste of human talent, i.e., not actively involving people in improving their own work environment.

Unlike other more rigid or hierarchical management models, Lean Management seeks to empower teams, encourage problem solving where they occur, and apply visual tools

to detect inefficiencies immediately. Its purpose is to create fluid, stable, and flexible workflows that can adapt to real demand and reduce unnecessary variability.

In the Factory Lab environment, where real production processes are simulated for educational purposes, Lean Management is the conceptual framework of reference. This work is framed within that philosophy, as it seeks to implement concrete solutions -such as the E-Kanban system, the use of on-demand replenishment and the automation of transportation- that reduce errors, improve efficiency and generate educational value for the students who interact with the system.

2.2 Lean Manufacturing

Lean Manufacturing is the practical application of Lean Management principles to the field of industrial production. Derived directly from the TPS, Lean Manufacturing aims to produce only what is necessary, at the right time and with the minimum number of resources, while ensuring quality and process flexibility [2]. While Lean Management establishes a transversal management philosophy, Lean Manufacturing focuses on the design of efficient and stable processes within the manufacturing environment [3]. It is based on the integration of a series of tools and methodologies to detect and eliminate waste, balance the workload and maintain a continuous flow of materials and information. Among the fundamental pillars of Lean Manufacturing are [2]:

- **Just-In-Time (JIT):** produce only what is needed, when it is needed, and in the required quantity. This allows us to reduce inventories, minimize lead times, and respond with agility to real demand.
- **Jidoka (automation with human supervision):** incorporate quality control mechanisms at each stage of the process to detect errors immediately and prevent the spread of defects.
- **Kaizen:** Continuous improvement applied to processes, equipment, and people.
- **Andon and visual systems:** tools that allow the visualization of process status in real time, which facilitates quick decision making and reduces reaction times to problems.

One of the most representative tools of Lean Manufacturing is the Kanban system, which acts as a material flow control mechanism based on a pull production logic. Instead of producing according to forecasts or stock, the Kanban system activates production only when there is a signal of actual consumption, which helps to synchronize the different stages of the process.

In addition to Kanban, there are other practices directly related to Lean Manufacturing that are applied in the work developed, such as on-demand replenishment methods (kitting and line stocking) and the automation of material transport, all of which are aimed at reducing waste and increasing the overall efficiency of the system.

In the context of this project, Lean Manufacturing provides the set of tools and operating principles upon which the automated replenishment system has been designed and implemented, adapted to an educational environment that replicates the conditions of a modern industrial assembly line.

2.3 Kanban System

One of the fundamental pillars of Lean Manufacturing is the Kanban system, developed by Toyota as part of the TPS. Its function is to regulate the flow of materials or tasks within a production process, so that each stage requests from the previous one only what it needs, at the right time and in the right quantity [2, 4]. The Japanese term Kanban literally means "visual signal", and that is precisely the essence of the system: using visual signals (such as cards) to control production and replenishment, rather than relying on centralized forecasts or instructions. This creates a pull system, where production is only triggered when there is actual demand. In addition to the use of physical cards, the Kanban system is supported by a series of visual tools that allow us to control the production flow in a clear and decentralized way. These tools include Kanban boards, coded cards, identified containers and visual light signals [2]. They all help to maintain an organized work environment, where any operator can identify the status of each process just by looking at it. The key to Kanban is its pull system nature, where actions are triggered by actual demand, not by prior planning. There are different types of Kanban cards according to their function. The two main ones are [2, 3]:

- Production Kanban: tells the upstream process to produce a specific quantity of a product.
- Withdrawal Kanban: authorizes the transfer of parts from a storage point or supermarket to the station that needs them.

These signals act in combination to coordinate production and material movement without the need for external orders, facilitating an agile, synchronized response without excess inventory.

As well as managing the replenishment of materials, the Kanban system plays an essential role in workflow control. The use of visual cards and signals allows each station to work only when necessary, avoiding unnecessary accumulation of Work In Process (WIP) and synchronizing the production rhythm between consecutive processes. The goal is not to plan each step-in advance, but to stabilize the workflow dynamically and visually. In the author's own words: "Kanban is not a planning tool; it is a control tool. Its purpose is to limit work-in-process and highlight problems in real time." [2]

This idea translates into what Liker calls "controlled autonomy", where each operator or station makes decisions based solely on the information provided by the visual system. If a card arrives at a station, it works; if it doesn't, it waits. This simple but powerful logic allows bottlenecks, interruptions or overloads to be detected without the need for complex monitoring [2].

In addition, by limiting the number of active cards in the system, Kanban explicitly limits the work in progress and facilitates a level flow, a fundamental aspect in the concept of heijunka (production leveling). All this contributes to creating a system that is more agile, predictable and better adapted to changes in demand.

In the context of this project, this flow control logic is present in the way the number of active orders is limited, station assignments are synchronized, and missions are enabled to be sent to the robot only when the system is available to receive them. This ensures an orderly operation, without overlapping, and faithfully reflects the spirit of a well-implemented Kanban system.

Benefits of the Kanban System:

The Kanban system offers multiple benefits that align with the principles of Lean Manufacturing and continuous improvement. One of its key advantages is that it eliminates the need for detailed, centralized planning, as each process responds only to actual demand through visual signals. This decentralized approach helps stabilize the production flow, making it more predictable and resilient to variations. Toyota used Kanban to "create a more flexible and efficient production system, reducing errors and downtime in the process." [2]

Kanban also contributes to reducing work in process inventory and waiting times, since materials and tasks only move when the downstream process is ready to receive them. By limiting WIP, the system naturally exposes bottlenecks and encourages their resolution — key elements of Lean thinking. Additionally, the visual nature of Kanban — through cards, containers, or boards—makes the status of production instantly visible to all stakeholders. This transparency facilitates better decision-making and immediate response to problems, supporting the Lean principle of *jidoka* (automation with human oversight).

Another essential benefit is that Kanban empowers operators to manage and regulate their own workflow, fostering autonomy and accountability at every level of the organization. Rather than relying on supervisors or planners, workers know what to produce and when, based on the movement of Kanban signals. This type of controlled autonomy, as described by Liker, encourages engagement and reinforces the culture of *kaizen*, or continuous improvement, which is fundamental in Toyota's approach to production.

Limitations of Traditional Kanban:

While the traditional Kanban system is highly effective in stable and repetitive manufacturing environments, it presents several limitations when applied to more dynamic, complex, or digitized contexts. As Liker (2004) explains, "the Kanban system works very well in stable, repetitive environments, but in highly variable or fast-changing situations it can become inflexible." This rigidity can be problematic in production systems with frequent product changes, fluctuating demand, or the need for real-time adaptability.

Additionally, the physical nature of Kanban cards introduces operational risks, "physical Kanban cards are simple and effective, but they can get lost, damaged, or delayed, causing disruption in the pull flow." These interruptions compromise the reliability of the system and often require manual intervention [3]. Moreover, traditional Kanban offers no digital traceability or automated historical records, which limits the ability to analyze performance or improve processes based on data, "manual systems often lack traceability. When problems arise, it's hard to understand what went wrong and when." [5]

Finally, conventional Kanban systems are not designed to integrate with modern technologies such as robotics, cloud platforms, or digital dashboards. This lack of interoperability hinders their application in Industry 4.0 environments, where systems must communicate and adapt in real time. These challenges have led to the development and adoption of Electronic Kanban (E-Kanban) systems, which address many of the shortcomings of their physical counterparts.

2.4 Electronic Kanban (E-Kanban)

As manufacturing environments become increasingly automated and complex, the traditional Kanban system—based on physical cards and containers—shows clear limitations in terms of speed, scalability, and traceability. In response to these challenges, the Electronic Kanban (E-Kanban) system has emerged as a digital evolution of the original concept, maintaining its pull logic while introducing real-time communication and data integration. An E-Kanban system replaces physical signals (such as cardboard cards) with electronic triggers that can be generated through various input devices, including [6]:

- Push buttons connected to microcontrollers (e.g., Raspberry Pi, Arduino);
- Barcode or Quick Response (QR) code scanners;
- Radio-Frequency Identification (RFID) readers;
- Digital interfaces or touchscreens;
- Automated sensors that detect inventory levels.

Once a signal is triggered, the system can send the request instantly to the appropriate location (e.g., warehouse, production line, robot) via a local network, a cloud-based platform, or industrial protocols like Message Queuing Telemetry Transport (MQTT) or Open Platform Communications Unified Architecture (OPC UA). This enables real-time monitoring of demand, task assignments, and inventory movements, greatly improving responsiveness and accuracy.

One of Toyota’s key innovations was its use of visual and immediate signals to synchronize production [2], and E-Kanban builds directly upon this principle. The difference is that these signals are now digital, traceable, and capable of integration with broader enterprise systems such as ERP, MES, or even autonomous mobile robots.

Also the importance of flow transparency and waste elimination [3], both of which are enhanced in E-Kanban by the ability to store and analyze historical data, identify delays, and automate responses to shortages. For example, delayed replenishment can trigger a warning notification, update a dashboard, and even launch a predefined workflow without human intervention.

In this project, the E-Kanban logic has been implemented using physical buttons and barcode scanners connected to a Raspberry Pi, which acts as the controller. These signals are interpreted by a Streamlit-based application [7], which updates the system state, manages station availability, and sends real transport missions to a mobile robot (e.g., MiR). This eliminates manual transport and ensures an automated, responsive, and scalable flow between stations —demonstrating the potential of E-Kanban within a smart factory environment.

2.5 Replenishment Methods

In any production system, the timely and accurate delivery of materials to the assembly line is essential to maintaining flow, avoiding delays, and ensuring product quality. Within the Lean Manufacturing philosophy, the objective is to supply the right parts, in the right quantity, at the right place and time — eliminating excess inventory, unnecessary

movement, and waiting times. Two of the most used methods for material supply are Kitting and Line Stocking.

2.5.1 Kitting

Kitting consists of pre-assembling all the parts needed to complete a product or subassembly into a single kit, which is then delivered to the operator or workstation. Each kit contains only the components required for a specific task, product variation, or customer order. This method is particularly useful in environments with a high product variety, where operators need different parts for each production unit. By preparing the kit in advance (usually in a logistics or preparation area), the time spent searching, selecting, or verifying components on the line is minimized. Kitting contributes to the reduction of operator errors, increases productivity, and simplifies the line layout. However, it also requires greater planning effort, space for kit staging, and coordination with logistics teams [3].

2.5.2 Line Stocking

Line Stocking refers to the practice of delivering components in bulk or batches directly to the production line, where operators select and use the parts as needed [8]. This method is simpler in terms of logistics but may lead to larger inventories along the line, potential confusion when product variants are involved, and more operator movement. This method is well-suited to standardized or high-volume production, where parts are common across multiple products and replenishment cycles are predictable. Dennis said "the line should never be a warehouse," yet many factories fall into this trap when line stocking is not properly managed [9].

2.5.3 Comparative Analysis and Practical Application

Kitting and Line Stocking are two widely used material supply strategies in manufacturing, each with its own advantages, limitations, and ideal use cases. The choice between them depends on factors such as product complexity, variability, space constraints, and the degree of flexibility required on the shop floor.

In Kitting, all the components required for a specific assembly task are grouped into a kit and delivered as a single unit. This method is particularly beneficial in high-mix, low-volume production environments, where each product requires a different set of parts and the assembly process is prone to human error. By providing all parts in one organized tray, kitting reduces cognitive load on operators, minimizes picking mistakes, and improves traceability. For example, in an assembly line producing custom-configured medical devices or small-batch automotive variants, kitting ensures that the exact set of components is available at the right time and place, supporting quality and consistency.

On the other hand, Line Stocking involves keeping a supply of standard components at the workstation, with replenishment triggered when individual trays or bins run low. This method is better suited for high-volume, standardized production, where parts are reused across multiple products and the operator is familiar with the required components. For example, in an electronics assembly plant where resistors, capacitors, and screws are used across all product variants, line stocking simplifies logistics by reducing the need

to pre-sort items into kits and allows more direct interaction with the inventory. It also reduces the workload of the warehouse, as no pre-assembly of kits is required.

2.6 Mobile Robots in Industrial Logistics

The adoption of AMR in industrial logistics has transformed the way materials are handled inside factories and warehouses. These robots are designed to transport goods without fixed routes, using onboard intelligence to navigate through complex environments. Their emergence aligns with the principles of Industry 4.0, where flexibility, decentralization, and data-driven decision-making are critical.

Unlike traditional Automated Guided Vehicle (AGV), which rely on magnetic tapes, QR codes or embedded tracks for navigation, AMR use Simultaneous Localization and Mapping (SLAM) combined with Laser Imaging Detection and Ranging (LiDAR) sensors, depth cameras, and sensor fusion algorithms to map their environment and move freely within it. This capability allows for greater adaptability in dynamic or reconfigurable spaces — a core requirement in modern Lean factories. Mobile robots serve multiple purposes within industrial settings [10]:

- Transporting raw materials, components, and finished goods between storage, assembly lines, and packaging zones.
- Enabling JIT delivery by responding in real time to production demands.
- Reducing non-value-added operations, such as unnecessary walking or manual pushing of carts.
- Enhancing worker safety and ergonomics, particularly in environments where heavy or repetitive manual handling is involved.

AMR offer “a new paradigm in intralogistics, enabling dynamic reallocation of transport resources in response to real-time system states.” [10] This adaptability is particularly beneficial in pull-based systems, where parts are only supplied when needed, eliminating overproduction and excess inventory. Moreover, AMRs support intelligent material flow orchestration when integrated with MES, ERP systems, or digital Kanban boards. This allows for:

- Automatic initiation of transport tasks based on production orders or sensor events.
- Real-time tracking and traceability of material movements.
- Reduction in operational costs and improved space utilization.

Studies emphasize that AMRs are “key enablers of the smart factory vision,” not only because of their autonomy, but also due to their interoperability with digital platforms, which supports decision-making and predictive control [11].

In Lean Manufacturing environments — especially those operating with E-Kanban systems or high-mix, low-volume production — AMRs contribute to balanced flow, reduction of stockouts, and shorter response times, aligning with lean goals of waste elimination and continuous improvement.

2.6.1 The MiR Robot: Architecture and Industrial Applications

One of the most prominent solutions in the autonomous mobile robotics field is the MiR platform [12, 1]. MiR robots are designed to automate internal transport tasks in manufacturing, logistics, and laboratory environments, reducing the need for human-operated forklifts, carts, and pallet trucks.

What distinguishes MiR robots from other AMRs is their focus on plug-and-play deployment, user-friendly mission programming, and a robust, scalable architecture that supports both single-robot applications and full-fleet coordination. These features make them particularly suitable for dynamic and evolving production environments.

Architecture and Core Features

Each MiR unit integrates a combination of advanced sensing and navigation systems:

- **360° LiDAR scanners** for obstacle detection and real-time environment mapping.
- **3D cameras** to detect floor-level objects and avoid collisions.
- **SLAM-based navigation** for self-localization without physical markers or magnets.
- **Onboard Linux OS**, running a Representational State Transfer (REST) full Application Programming Interface (API) that allows remote mission control and integration with external systems.
- **Top modules** (e.g., racks, conveyors, robot arms) that allow MiRs to adapt to different transport needs.

These robots use dynamic path planning and obstacle avoidance to navigate efficiently through shared spaces, even in the presence of people or unexpected obstacles.

Table 2.1 provides a comparative overview of the most common categories of industrial robots, highlighting their key characteristics, typical applications, and advantages.

Applications in Industry

In real-world applications, MiR robots are used for [1, 10]:

- Supplying materials to assembly lines in response to production signals.
- Collecting finished goods and transporting them to packaging or storage.
- Automating Kanban-based replenishment loops, where each workstation sends a signal to restock specific trays or components.
- Synchronizing flow between workstations, especially when there is a need to avoid overproduction or congestion.

The MiR Fleet software adds an additional layer of intelligence, allowing multiple robots to operate simultaneously, assign tasks dynamically, avoid traffic bottlenecks, and balance workloads. This feature is especially relevant in large or multi-zone factories, where manual coordination of robot routes would be inefficient. Furthermore, the MiR system is designed to integrate with digital manufacturing environments, such as ERP, MES, or E-Kanban systems, using standard interfaces like REST or OPC UA. This makes it possible to implement event-driven logistics, where robots respond automatically to production demands, sensor triggers, or low-inventory warnings.

Feature	MiR Robots (AMR)	Fixed Industrial Robots	Traditional AGVs
Type of robot	Autonomous Mobile Robot (AMR)	Fixed robotic arm	Guided vehicle using physical paths
Navigation capability	SLAM, LiDAR sensors, dynamic routing	Do not move, fixed position	Fixed routes with tape or reflectors
Task flexibility	High	Limited to pre-programmed tasks	Low, repetitive tasks
Human interaction	Safe, designed for collaboration	Require segregated areas	Limited safety
Installation and setup	Quick, no fixed infrastructure needed	Complex, fixed setup	Requires physical guiding infrastructure
Load capacity	Up to 500 kg or more	Depends on the arm model	From small to heavy loads
Autonomy	Rechargeable battery, auto-charging	Fixed power supply	Limited battery life
Work environment	Flexible: factories, warehouses, hospitals	Fixed production zones	Warehouses with predefined routes
Scalability	High, easy to add more units	Low	Moderate
Navigation technology	SLAM, LiDAR, 3D cameras	Not applicable	RFID, laser, magnetic tape
Example use cases	Internal logistics, autonomous transport	Welding, assembly, pick & place	Repetitive load transportation

Table 2.1: Comparison between MiR robots, traditional industrial robots, and AGVs. [10, 12]

Chapter 3

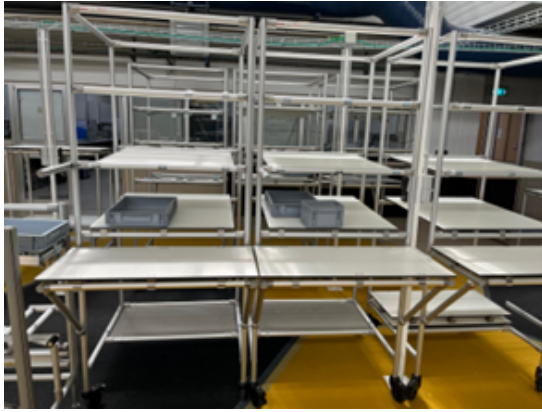
Analysis of Supply Strategies: Kitting and Line Stocking

In modern manufacturing environments, the efficiency of material supply systems plays a crucial role in overall production performance. Among the most widely used strategies for delivering components to assembly lines are kitting and line stocking. This chapter analyzes both approaches in terms of their operational characteristics, benefits, and limitations, as well as their impact on workflow organization and flexibility within the production system.

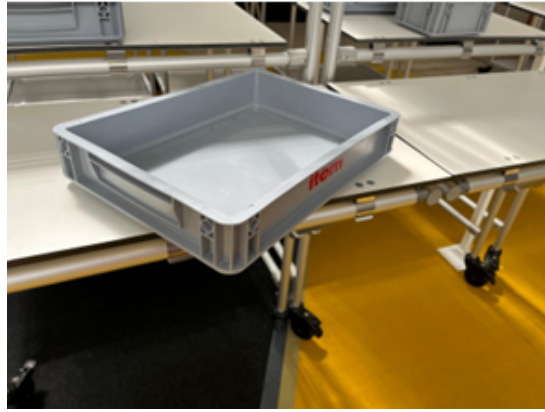
3.1 Physical Setup

The project has been developed entirely within the Factory Lab facilities, specifically in the Lean Manufacturing simulation area. The current elements are:

- **Workstations:** Each workstation consists of a main worktable accompanied by a set of interchangeable shelving units designed to temporarily hold trays containing the components involved in the production process (see Figure 3.1a). These trays can be positioned at different vertical levels depending on operational needs. The shelving modules include both flat platforms, which allow trays to remain stationary during assembly tasks, and gravity-fed or rail-based shelves, which enable trays to be stacked in sequences supporting an orderly and efficient material flow. All core manufacturing operations are performed on the workbench itself, which also serves as the reception point for incoming parts.
- **Trays:** A set of trays is used to store and transport the different components involved in the assembly process (see Figure 3.1b). These trays play a critical role in the organization of the workflow, as they serve as the primary units for transferring materials between the warehouse area and the workstations.
- **Storage Racks:** The FL is equipped with modular storage racks that serve as the main structure of the warehouse. These racks feature multiple storage cells equipped with mobile rails, allowing for organized placement and smooth handling of the trays containing various parts (see Figure 3.1c). Each unit is configured with eight storage cells, arranged in two vertical columns and four horizontal rows, forming a structured and efficient layout for storing and retrieving materials during the process.



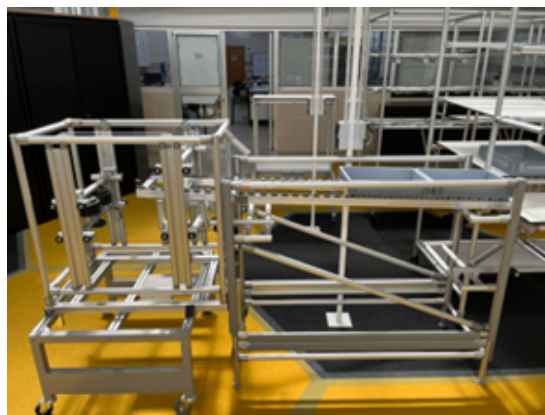
(a) Workstations.



(b) Trays.



(c) Storage racks.



(d) Karakuri.



(e) Flat shelves.

Figure 3.1: Available elements at Factory Lab on the Lean Room.

- **Karakuri Systems:** The FL incorporates various karakuri mechanisms, which are purely mechanical systems designed to move trays between different locations without the need for electrical power. One particularly noteworthy configuration enables trays to be loaded from the top and retrieved from the bottom (see Figure 3.1d), thereby implementing a First In, First Out (FIFO) storage strategy. These passive systems support Lean principles by facilitating material flow in an ergonomic and energy-efficient way.
- **Mobile Rack for Tray Handling:** As part of the material flow system, a mobile rack with wheels has been included. This structure consists of flat, rail-free shelves designed to hold trays containing components temporarily (see Figure 3.1e). It is primarily used by the control operator, who places the trays after preparing them for delivery. The trays stored here are organized according to pending requests or replenishment cycles.

It is worth noting that both this mobile rack and the previously mentioned karakuri FIFO system are intended to be interfaced with the MiR mobile robot, which will autonomously collect trays from these points and transport them to the corresponding workstation as part of the replenishment strategy described in Chapter 4. This integration supports the Lean principle of material flow automation while maintaining flexibility in tray handling.

Finally, the FL is also equipped with various modular components [13] which can be used to reconfigure, expand, or customize the physical structure of the workstations, shelving units (see Figure 3.2), or support frames as needed. Once the main physical elements are understood, the next step involves defining the functional zones and organizing the spatial distribution, allowing for a clear overview of the layout and flow of the simulated plant.

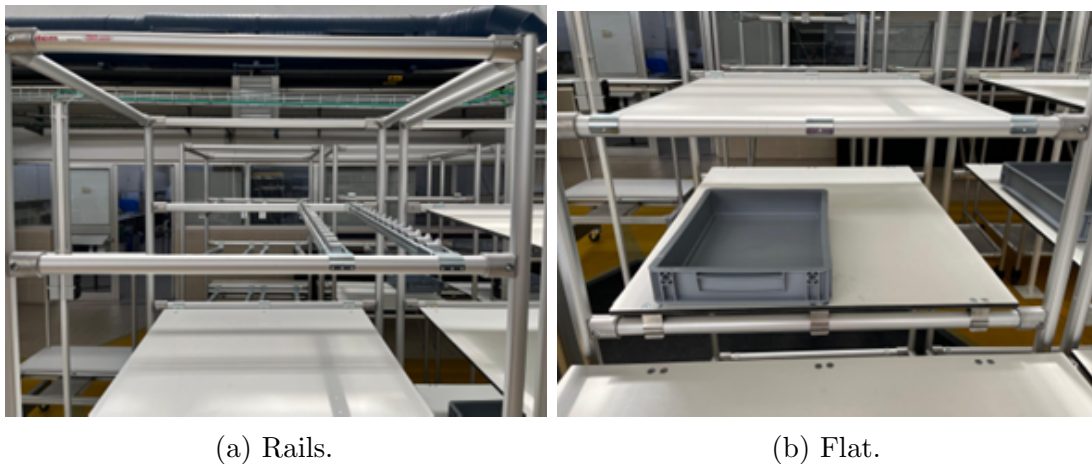


Figure 3.2: Types of shelves.

Functional Zone Layout

To support an organized and efficient material flow, the physical space of the FL is divided into two main zones. On one side, the storage and preparation area contains the modular storage racks, the mobile tray rack, and the computer running the Streamlit interface. In this area, the control operator is responsible for preparing trays according to

the orders received in real time from the system. Once the trays are ready, they are placed on the mobile rack awaiting collection. On the other side are the workstations (WS1 and WS2), where the operators carry out the assembly or production tasks. Each station is equipped to receive trays. The connection between both areas is dynamically supported by the mobile robot, which moves freely throughout space and delivers materials based on the requests and decisions made by the system and the operators. This flexible layout enables efficient synchronization between supply and production, following the principles of Lean Manufacturing.

3.2 Restocking Processes

The goal is to develop an E-Kanban system to manage the replenishment of parts from the warehouse to the workstations. At the workstations, operators will assemble products that require specific parts. An operator will be responsible for handling the trays with parts; however, the transportation between the warehouse and the workstations will be carried out by a MiR robot. After delivering the parts, the operator will collect the empty trays to return them to the warehouse.

This approach ensures that workstations always have the necessary parts to continue production, as the warehouse operator will continuously perform the replenishment cycle with the assistance of the MiR robot for transport. The main challenge the system must address is enabling operators at each workstation to quickly and remotely notify the warehouse of depleted parts that need to be restored. This allows the warehouse system to process these signals and guide the replenishment operator in selecting and delivering the correct parts to the respective stations.

Additionally, the system must handle the collection of empty trays, which is part of the replenishment cycle carried out by the warehouse operator. The operator should be able to easily identify which tray to collect from each workstation.

Since future updates and additional functionalities are planned—utilizing the data generated and stored by the system—the solution cannot be commercial but must be fully developed from scratch. It should be robust, support effective data management, and be flexible enough to allow easy expansion of elements such as workstations and storage racks.

For this project, the system will be designed and tested to support two workstations, each with one operator, and one storage rack in the Factory Lab, which will have eight different storage cells available. To evaluate the behavior of the replenishment system and the logistics architecture, a real assembly process has been defined using pneumatic components [14]. The selected setup includes a fixed collection of parts that serve as the basis for building three different product variants. All three product variants share a common pneumatic assembly base composed of five essential components: the cylinder body, front and rear end caps, the piston, and the piston rod. These parts form the internal structure of the actuator and are assembled in the same way for every product. From this common foundation, each variant is completed by adding different external accessories (see Figure 3.3) that define its final configuration.



Figure 3.3: Mounting accessories.

- **Product A** – Base pneumatic cylinder The simplest configuration consists only of the cylinder with pneumatic fittings. No additional accessories are included in this version (see Figure 3.4a).
- **Product B** – Cylinder with base mounting brackets. Based on Product A, this variant includes two HNA-40 foot brackets (see Figure 3.3a) mounted at the base of the cylinder to simulate structural attachment (see Figure 3.4b).
- **Product C** – Cylinder with guide and mounting plate. This configuration adds both a SG-M10x1,25 guide (see Figure 3.3b) and a SNCL-40 plate (see Figure 3.3c) to the base of the cylinder, representing a more complete subassembly (see Figure 3.4c).

These three variants were chosen to simulate production variability, test the flexibility of the replenishment methods, and evaluate the operator's ability to distinguish and assemble multiple product types using barcodes, visual aids, and interactive feedback.

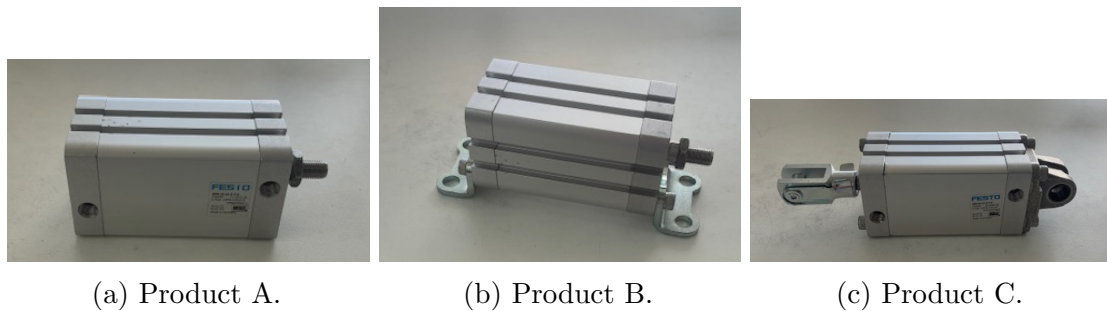


Figure 3.4: Products variants.

3.2.1 Kitting

Kitting is a logistics and production strategy that involves pre-assembling all the necessary components into kits before they reach the assembly line [15, 16]. This ensures that operators have exactly the parts they need at the right time and place, minimizing delays and optimizing workflow efficiency. The main goal of kitting is to streamline assembly operations by reducing downtime caused by part shortages or excess inventory buildup.

In this system, kitting is directly linked to the company's sales and order management platforms, allowing real-time updates of part demand as customer orders are received.

This direct connection means that any purchase or demand for parts triggers an immediate update in the production requirements without manual data entry or intermediary processes, implementing a true JIT manufacturing flow.

Once a kitting demand is registered, the warehouse operator prepares the kits by gathering all required components. These kits are then delivered autonomously to the production line using a MiR mobile robot, ensuring consistent and timely material flow.

At Workstation 1, the tray delivered by the robot contains all parts needed for the first stage of assembly, carefully organized for easy retrieval by the operator. After completing the assembly step, the operator sends a digital completion signal to the system. This signal plays a critical role in managing the flow of trays through the stations by enforcing a maximum number of active trays per workstation. Setting a maximum tray limit per workstation is essential to maintain smooth production flow and avoid bottlenecks. For example, if Workstation 1 produces parts too quickly and sends many trays forward without limitation, Workstation 2 may become overwhelmed, leading to an accumulation of unfinished products and possible congestion. Conversely, if Workstation 2 is waiting for trays from Workstation 1, it results in idle time and decreased throughput. The tray limit helps balance the pace between stations, preventing both overload and starvation scenarios, and thus optimizing the overall assembly line efficiency.

Once the operator at Workstation 1 signal is complete, they manually pass the tray containing the partially assembled product along with the next kit to Workstation 2. The operator at Workstation 2 performs their assembly tasks, then similarly sends the signal completion and leaves the fully assembled product on the tray.

Finally, the warehouse operator collects finished products and empty trays from the workstations, closing the replenishment cycle and ensuring continuous operation.

A critical aspect of the system is the transmission of a completion signal from each workstation to the central control unit. This signal serves as a real-time indicator of the workstation's status and is essential for managing the flow of trays throughout the assembly line. By monitoring these signals, the system can track how many trays are currently active at each station and enforce predefined limits. This mechanism helps balance the pace between stations, prevents excessive buildup of work-in-progress, and ensures that downstream stations are neither overwhelmed nor left waiting. In essence, these signals enable dynamic, real-time coordination across the production line, maintaining smooth and efficient operation.

Design Criteria System must Fulfill

- **online integration with demand sources:** Seamless connectivity with sales and order platforms to dynamically reflect actual market demand without manual intervention.
- **Autonomous and reliable material transport:** Use of automated transport (MiR robot) for timely and accurate delivery of kits to each workstation.
- **Efficient tray and workflow management:** Implementation of a maximum tray limit per workstation to balance production speed and prevent bottlenecks or idle time.
- **Clear communication and signaling:** Operators must be able to send completion signals reliably to update the system and control workflow dynamically.

- **Scalability and flexibility:** The system should allow easy addition or removal of workstations and storage units without requiring major redesigns.
- **Robust data management:** Accurate tracking and storage of production data to support monitoring, analysis, and future improvements.

3.2.2 Line Stocking

Line stocking is a logistics method focused on supplying individual component types to workstations as needed [8], instead of delivering complete sets of parts in advance. This strategy supports continuous production flow by ensuring that high-consumption parts are always available at the assembly points.

The demand is defined as a list of final products that need to be assembled. Based on this list, the system determines the components required at each workstation. Although the operators need to know how to perform their assigned tasks, the process is simplified by the fact that each workstation only receives the specific components relevant to its sub-process. This setup minimizes complexity for the workers and ensures that they are only presented with the materials needed for their operation, reducing the risk of errors or incorrect assembly. To enable the workflow, a first wave of trays is sent to the workstations, each containing a sufficient quantity of the needed components. This initial delivery is critical, as it allows operators to begin working without delay, and must include enough parts to avoid production stoppages before replenishment can occur.

The global assembly process follows a workflow similar to the kitting mode: each workstation passes its completed sub-assembly to the next station, forming a continuous production line. When a workstation runs out of a specific component, the operator must notify the warehouse operator, who will then handle the replenishment by delivering a new full tray and collecting the corresponding empty one. Once the final workstation completes the assembly of the end product, the finished units are placed into designated empty trays. These are then collected by the warehouse operator to be stored or moved to the next phase in the logistics chain.

This method offers several advantages. Firstly, it eliminates the need to define a maximum number of trays per workstation, as the system maintains a constant tray flow: the number of trays in circulation remains equal to the initial number dispatched at the beginning of the cycle. This simplifies inventory tracking and reduces the risk of tray overflow or misplacement. Secondly, the warehouse operator is responsible for analyzing the predefined production demand in order to determine the appropriate quantity of components to include in each replenishment tray. This decision is critical to ensure uninterrupted production while avoiding unnecessary overstocking at the stations.

Design Criteria System must Fulfill

- Each workstation must be capable of sending replenishment requests in an easy and intuitive manner for the operator, minimizing time loss during production.
- The central operator must be able to receive these signals and quickly identify both the component requested and the originating workstation, allowing for a timely response.

-
- The system must be capable of detecting invalid or erroneous signals sent from the workstations. In such cases, it should alert the central operator and provide guidance to help the respective station correct the issue in real time.
 - As kitting, use of automated transport (MiR robot) for timely and accurate delivery of trays to each workstation.

Chapter 4

Implementation and Testing

This chapter presents the implementation and testing of the proposed system, covering both hardware and software components. The integration process is described in detail, highlighting how each element contributes to the overall functionality. Once the system is assembled, a series of tests are conducted to validate the application’s behavior and its performance in a real-world industrial scenario, including physical interaction with the devices and the evaluation of user workflows.

4.1 Hardware Setup and Deployment

This section describes the hardware configuration used in the implemented system. While the physical infrastructure available in the Lean Manufacturing zone of the Factory Lab — previously described in Chapter 3 — served as the foundation, this project involved the selection, integration, and deployment of additional components to support the periodic control system, automation, and user interaction.

Each selected device was chosen based on its functional role, reliability, and ease of integration into the overall system. Additional consideration was given to their compatibility with industrial environments and their ability to support the operational requirements of the project. The following subsections present the key hardware elements used in the implementation, explaining their technical capabilities, integration into the system, and the specific reasons for their selection. The goal was to create a distributed yet coordinated architecture that supports responsive workflows, scalability, and flexible material handling.

4.1.1 Raspberry Pi 4 Model B as Distributed Control Nodes

The Raspberry Pi 4 Model B (see Figure 4.1) was chosen as a fundamental element of the system due to its computational power, compact size, and flexibility for interfacing with peripherals [17, 18]. Three units were deployed, each assigned to a specific control function within the distributed system architecture.



Figure 4.1: Raspberry Pi 4 Model B.

One Raspberry Pi acts as the central controller for visual signalling, generating lighting instructions for the Neopixel LED strips located at the workstations. These signals guide the operator by indicating task status, completion, or product requests in real time.

The remaining two Raspberry Pis are positioned at Workstation 1 and Workstation 2, where they serve as local input nodes by handling barcode scanning operations. Each is connected to a Universal Serial Bus (USB) barcode scanner, captures the scanned input, and transmits the relevant information to the central application for processing and decision-making.

The Raspberry Pi 4 Model B is particularly well-suited for this application thanks to its strong technical specifications:

- Quad-core Cortex-A72 (ARM v8) 64-bit processor at 1.5 GHz, enabling parallel processing and responsive control tasks.
- 2 to 8 GB of LPDDR4-3200 Random Access Memory (RAM), depending on the configuration, suitable for multitasking and concurrent operations.
- Dual-band Wireless Fidelity (Wi-Fi) (2.4GHz and 5GHz) and Bluetooth 5.0, providing multiple communication options for flexible integration.
- Four USB ports, including two USB 3.0, allowing fast and reliable peripheral connections such as barcode scanners.
- 40-pin General Purpose Input/Output (GPIO) header, supporting direct interaction with sensors, actuators, and control systems.
- Broad support for development environments like Python, C/C++, and Node.js, and compatibility with libraries for industrial control, vision, and networking.

It is important to know that the Raspberry Pi 4 Model B is a versatile single-board computer originally designed for educational purposes, prototyping, and desktop applications. This means, its standard configuration is not inherently suited for deployment in industrial production environments, where that typically expose electronic devices to challenges including electromagnetic interference, mechanical vibrations, extreme temperature variations, dust, humidity, and other harsh conditions. Due to these factors, the Raspberry Pi 4 in its default form cannot be considered industrial-grade hardware. Prolonged exposure to the aforementioned adverse conditions may result in hardware degradation or failure.

In the context of this project, which is carried out within a controlled laboratory environment simulating factory conditions, these limitations are not critical, therefore, when intended for use in factory settings, additional protective measures must be implemented to ensure operational reliability and longevity [19].

4.1.2 Barcode Scanner

The Eyoyo 2D USB Bluetooth Ring Barcode Scanner (see Figure 4.2) is a versatile and ergonomic device designed to enhance operational efficiency in industrial and logistics environments. Its compact ring form factor allows the operator to wear the scanner comfortably on a finger, providing hands-free scanning capabilities and reducing fatigue during extended use.



Figure 4.2: Eyoyo 2D Scanner.

Key Features Include:

- **Wireless and wired connectivity:** The device supports both Bluetooth wireless connection and USB wired connection, enabling flexible deployment according to the operational environment and infrastructure availability. Bluetooth typically offers stable connections within a certain radius (commonly up to 10 meters).
- **Ergonomic design:** The ring shape and lightweight construction, weighs only 30g (1.05oz), optimize comfort and usability, allowing seamless integration into the workstation and reducing operator strain. It is also designed for both left and right-hand use, with a 330° adjustable head to accommodate various scanning angles.
- **Compatibility and versatility:** The scanner is capable of reading a wide range of barcode symbologies, including 1D, 2D, QR, PDF417, and Data Matrix codes, including damaged or poorly printed barcodes, making it suitable for diverse applications such as inventory management, order picking, and assembly verification.
- **Easy integration:** The USB interface supports plug-and-play functionality for quick setup, while Bluetooth pairing provides convenient wireless operation without complex configuration.

- **Battery life and charging:** Equipped with a 450mAh rechargeable battery, providing up to 8 hours of continuous operation on a full charge. Battery endurance and convenient charging methods are important factors to ensure uninterrupted use during shifts.

For this project, the scanner will be connected to the Raspberry Pi using the 2.4 GHz wireless connection through the included USB receiver, which functions similarly to a wireless mouse receiver. This setup ensures stable, reliable communication without the complexity of Bluetooth pairing, and the USB receiver is directly plugged into the Raspberry Pi. This 2.4 GHz wireless connection via the USB receiver typically offers stable communication within approximately 10 to 15 meters indoors. This range may vary depending on environmental obstacles and electromagnetic interference common in industrial settings. For our application in a more controlled environment, it is more than sufficient.

4.1.3 Pick to Light System

The WS2812B Neopixel LEDs are individually addressable RGB LEDs widely used in educational and prototyping projects (see Figure 4.3) due to their ease of use, vibrant color output, and flexible control. Their visual appeal and dynamic lighting capabilities make them particularly attractive for students learning embedded systems and automation.

In this project, these LEDs are employed to implement a Pick to Light system within the storage rack of the warehouse. The LEDs serve as intuitive visual indicators that guide operators by illuminating specific picking locations, thereby improving picking accuracy and operational efficiency.

It is important to note that WS2812B LEDs are not industrial-grade components. While ideal for laboratory and demonstration environments, their design and robustness are insufficient for harsh industrial conditions, where factors such as temperature extremes, dust, and mechanical stress require more rugged hardware. For real industrial deployment, the LEDs would need to be replaced with components rated for industrial use to ensure durability and reliability.



Figure 4.3: WS2812B LEDs.

Pick to Light Systems

Pick to Light is a widely adopted order fulfillment technology that uses light indicators to direct warehouse operators to the correct locations for picking or replenishment. This system reduces errors and speeds up the picking process by providing clear, immediate visual cues. Pick to Light systems enhance productivity and accuracy in complex logistics operations [20].

Connection to the Raspberry Pi

The WS2812B LEDs communicate via a digital control signal, typically a single-wire data line that carries timed pulses encoding color and brightness information for each LED in the chain. This protocol is timing-sensitive, requiring precise control of pulse widths to differentiate between binary '0' and '1'. One of the Raspberry Pi's GPIO pins is used to send this control signal to the LED strip.

Due to the relatively high current demand of the full LED array—56 LEDs total (7 LEDs per cell $\times$ 8 cells)—the Raspberry Pi's onboard 5V rail is insufficient to power the LEDs directly. Therefore, an external 5V power supply will be used to provide adequate and stable current to the LED strips. The ground (GND) of the Raspberry Pi and the external power supply will be connected together to ensure a common reference for the signal.

PLC and Buttons

For the Pick to Light system, the SIEMENS 3SU1150-0AB40-1BA0 push buttons (see Figure 4.4b) were selected due to their technical features that ensure durability and reliability in industrial environments:

- **Mechanical and Electrical Durability:** These push buttons have a mechanical lifespan of up to 10 million cycles and an electrical lifespan of 10 million cycles at 10 A, guaranteeing long-lasting performance in high-frequency applications.
- **Size and Mounting:** With an installation diameter of 22.3 mm, they fit perfectly within the dimensions of the storage rack, allowing for both aesthetic and functional integration.
- **Materials and Protection:** The actuator is made of green plastic, and the front ring is metallic with a shiny finish, providing a professional appearance and resistance to harsh conditions.
- **Connection and Contact Type:** Equipped with screw terminals for secure connections and a 1NO (normally open) contact type, suitable for signaling applications.

Since these push buttons do not include built-in illumination, it is necessary to design and fabricate custom protective enclosures for each button. These housings will protect the buttons from dust, moisture, and potential impacts, while also improving their visual integration within the storage rack, enhancing ergonomics and helping operators easily identify picking zones. A total of 8 buttons are installed, corresponding to each picking location within the storage rack.

The signals generated by the button presses are transmitted via wired connections to the PLC, which acts as the central controller for monitoring and processing these inputs [21]. The PLC used in this project is the Siemens S7-1200 1214AC model (see



(a) S7-1200 1214AC.



(b) 3SU1150-0AB40-1BA0.

Figure 4.4: PLC and Buttons.

Figure 4.4a), chosen for its reliability and integrated features suitable for small to medium automation tasks.

This PLC offers 14 digital inputs, sufficient to handle the number of buttons in the system. Each button is wired directly to an individual digital input on the PLC, with a common positive voltage line (L+) supplying 24 VDC, provided by the PLC's internal power supply. It is also necessary to connect the common ground (M) to complete the circuit and ensure proper operation.

4.1.4 Central Warehouse Computer

The central warehouse computer serves as the core system that integrates all hardware components, including the PLC, barcode scanners, and the Pick to Light system. It hosts the main software responsible for coordinating operations, managing inventory, and processing orders. Equipped with a visual display interface, this computer provides warehouse operators with real-time information and control, forming the primary workspace around which daily tasks are organized.

4.2 MiR100 Integration for Autonomous Transport

In order to simulate a realistic and autonomous internal logistics flow, the project integrates a MiR100 mobile robot (see Figure 4.5) into the production system. This robot enables the automatic delivery and retrieval of trays between the warehouse and the workstations, reducing manual transport tasks and ensuring a more synchronized and efficient material flow.

The following subsections describe the rationale behind the robot's selection, its technical capabilities, its integration with the control application, and the configuration of the missions that define its behavior within the system.



Figure 4.5: MiR100 charging station.

4.2.1 Overview and Role in the System

To automate the internal transport of trays between the warehouse area and the production workstations, a MiR100 mobile robot was integrated into the system. This robot is responsible for executing missions that move material carriers—either karakuri racks or transport carts—to the correct station, based on replenishment signals and production flow requirements.

The MiR100 was selected primarily because it was available within the Factory Lab and is fully compatible with the physical infrastructure already in place, including the karakuri FIFO system and the flat-shelf mobile carts used by the warehouse operator. Its ability to dock and transport these structures makes it a practical and flexible solution for simulating real intralogistics operations.

By automating this transport task, the system reduces the need for manual material handling, minimizes idle time between stations, and supports pull-based workflows, as defined in Lean Manufacturing principles. The robot interacts with the central control system to receive transport requests, and it is the warehouse operator who is responsible for giving the green light to the corresponding missions.

4.2.2 Technical Specifications of the MiR100

The MiR100 is an autonomous mobile robot developed by Mobile Industrial Robots (MiR), designed to automate internal transport tasks in a wide range of industrial and logistics environments. Its architecture is based on advanced sensors, SLAM-based navigation, and a modular design, making it highly adaptable to changing layouts and varied transport needs. The following table (see Table 4.1), summarizes the most relevant technical characteristics of the MiR100 [1, 22]:

Feature	Specification
Payload capacity	Up to 100 kg
Maximum speed	1.5 m/s (adjustable depending on safety zones)
Battery	Li-ion, 24V, ~10 hours runtime (depending on usage)
Charging	Automatic or manual via docking station
Navigation	Laser scanners (360°), 3D camera, gyroscope, encoders
Navigation method	SLAM (Simultaneous Localization and Mapping)
Obstacle avoidance	Real-time dynamic path planning with safety zones
Dimensions	Approx. 890 × 580 × 352 mm (L × W × H)
Weight	~62 kg
Top modules	Compatible with racks, carts, lifters, conveyors
Communication	REST API, Modbus, TCP/IP, Wi-Fi, I/O expansion
Fleet management	Supported via MiR Fleet (centralized multi-robot control)

Table 4.1: Main technical specifications of the MiR 100 autonomous mobile robot.

One of the key physical features of the MiR100 is its top lift module, a mechanical elevation platform integrated into the robot's chassis. This lift allows the robot to automatically raise and lower its upper surface (see Figure 4.6), enabling it to dock with and transport various structures such as flat transport carts or karakuri systems.

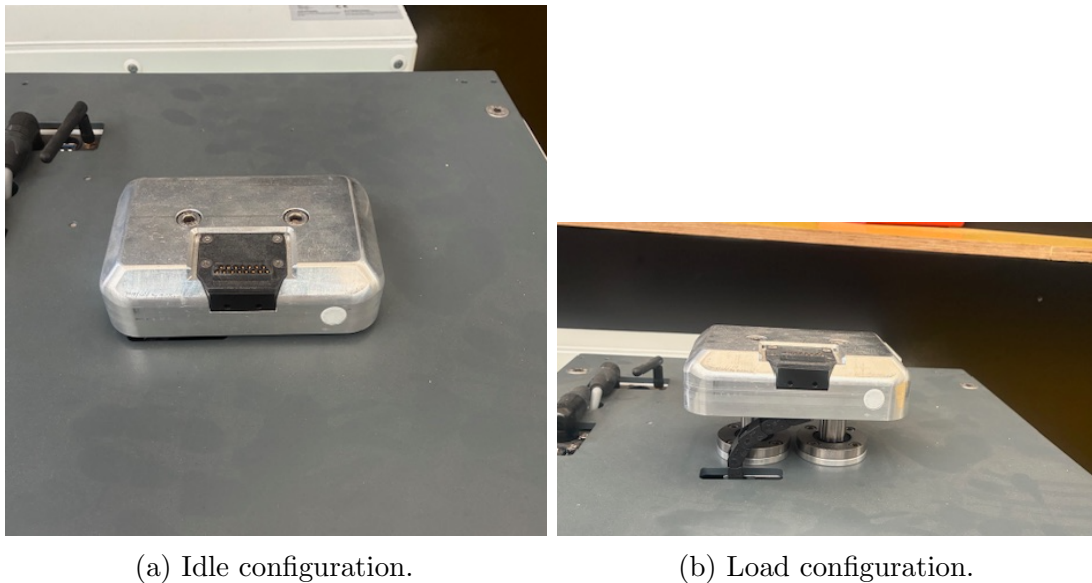


Figure 4.6: Operating sequence of the MiR100 lifting platform.

In this project, this functionality makes the MiR100 fully compatible with the tray racks and FIFO mechanisms used in the FL. The robot can approach a cart, raise its lift to secure it, transport it autonomously to the required location, and then lower the lift to release it, without human intervention.

4.2.3 Mission System and Implementation

The MiR100 robot operates using a flexible mission-based system, where each mission defines a predefined route and task, such as picking up or delivering a tray at a specific location. In this project, the central application is connected to the robot's mission

interface, enabling it to retrieve the complete list of available missions configured in the robot.

Through the visual display located at the warehouse operator's station, the system allows the operator to manually trigger the appropriate mission based on the current replenishment needs. This design offers a balance between automation and operator control, ensuring that missions are launched in response to real-time production demands while keeping the process transparent and adaptable.

Each mission was created using the MiR web interface, where destinations, waypoints, and actions can be graphically defined and assigned a unique identifier. The missions correspond to real material transport tasks in the Factory Lab environment, and were designed to support both Kitting and Line Stocking modes of operation.

The missions were designed according to the physical layout of the Factory Lab, taking into account the positions of the storage racks, workstations, and waiting zones (see Figure 4.7). Depending on the replenishment strategy (Kitting or Line Stocking), different racks and flat shelves are used.

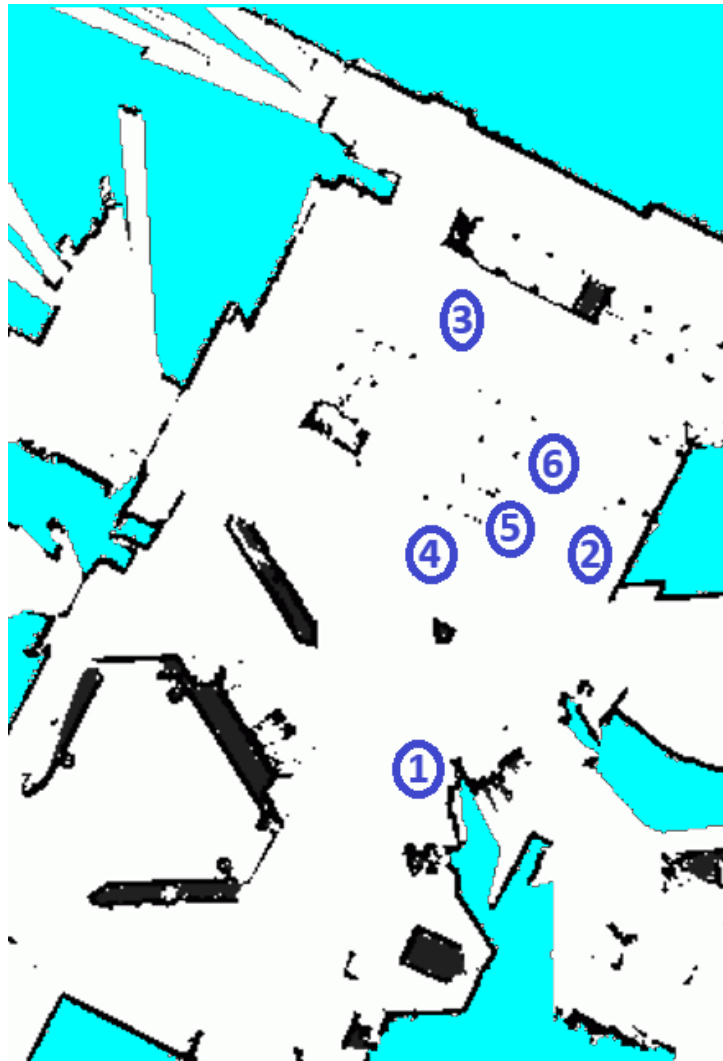


Figure 4.7: Scanned map of Factory Lab with Mir100 positions.

Legend of mission points:

- 1 – Charging Station.
- 2 – Pickup Station.
- 3 – Warehouse.
- 4 – Line Kitting.
- 5 – Workstation 1.
- 6 – Workstation 2.

Mission List

Table 4.2: List of missions configured in the MiR100 system

Mission Name	Destination	Docking Required
PICKUP SHELF	2	Yes
LEAVE SHELF	2	Yes
GO TO WAREHOUSE	3	No
GO TO LINE 1	4	No
WORKSTATION 1	5	No
WORKSTATION 2	6	No

To simulate realistic internal logistics within the Factory Lab, the system implements two transport workflows using the MiR100 mobile robot, corresponding to the Kitting and Line Stocking replenishment methods. In both cases, the robot is responsible for transporting trays between designated locations based on operator actions (see Table 4.2).

The diagrams below illustrate the typical sequence followed in each method, showing the robot's movement between key positions in the layout and the type of cart or structure used in each case. Real images of the robot performing the deliveries are also included to illustrate its integration with the physical carts used in the system.

Kitting

In the Kitting workflow (see Figure 4.8), the MiR100 robot begins each mission from its charging station, where it remains docked when idle. Upon receiving a new order, it moves to the docking point, where it automatically couples with an empty karakuri rack using its integrated lifting system (see Figure 4.9a).

The robot then travels to the warehouse area, where the operator loads a pre-assembled kit onto the rack (see Figure 4.9b). This kit consists of a tray containing all the components required for a specific product. Once loaded, the operator triggers the mission from the central interface, and the robot transports the karakuri to the production line.

Upon arrival, the robot places the karakuri at a designated position, allowing its mechanical system to release the tray automatically onto the first workstation (see Figure 4.9c). From there, the tray moves manually between stations as operators complete the required assembly steps. However, once all assigned kits have been consumed or a free space is detected in the warehouse rack, the MiR100 is assigned a new mission using a flat shelf cart. In this secondary cycle, the robot navigates through the workstations to collect empty trays and optionally retrieve completed products, returning them to the warehouse. This enables a continuous and balanced material flow, avoiding workstation saturation and minimizing idle time.



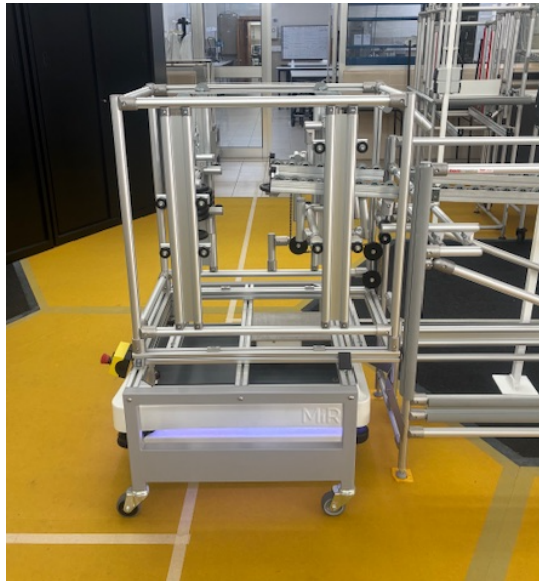
Figure 4.8: MiR100 Kitting route map.



(a) Docking karakuri.



(b) Karakuri positioned for loading kits.



(c) Delivering loaded karakuri.

Figure 4.9: Different MiR100 positions during Kitting route.

Line Stocking

In the Line Stocking workflow (see Figure 4.10), the MiR100 robot starts its mission by navigating to the docking point, where it couples with a flat transport cart (see Figure 4.11a) designed to carry individual trays. Once docked, the robot moves to the warehouse area, where the operator loads the trays (see Figure 4.11b) with the specific parts required by each workstation. These trays are typically dedicated to a single type of component and are labeled according to destination.

After loading, the robot initiates a delivery mission, visiting the required workstations sequentially to deposit the trays in their assigned positions. At each station (see Figure 4.11c), the corresponding tray is unloaded manually or placed by the operator on the station's rack.

During the same route or in a subsequent mission, the robot can also be used to collect empty trays left by operators or to retrieve trays containing completed products, thereby maintaining the flow of materials and ensuring workstation availability. This cyclical operation contributes to a smooth replenishment loop and supports real-time responses to production needs.

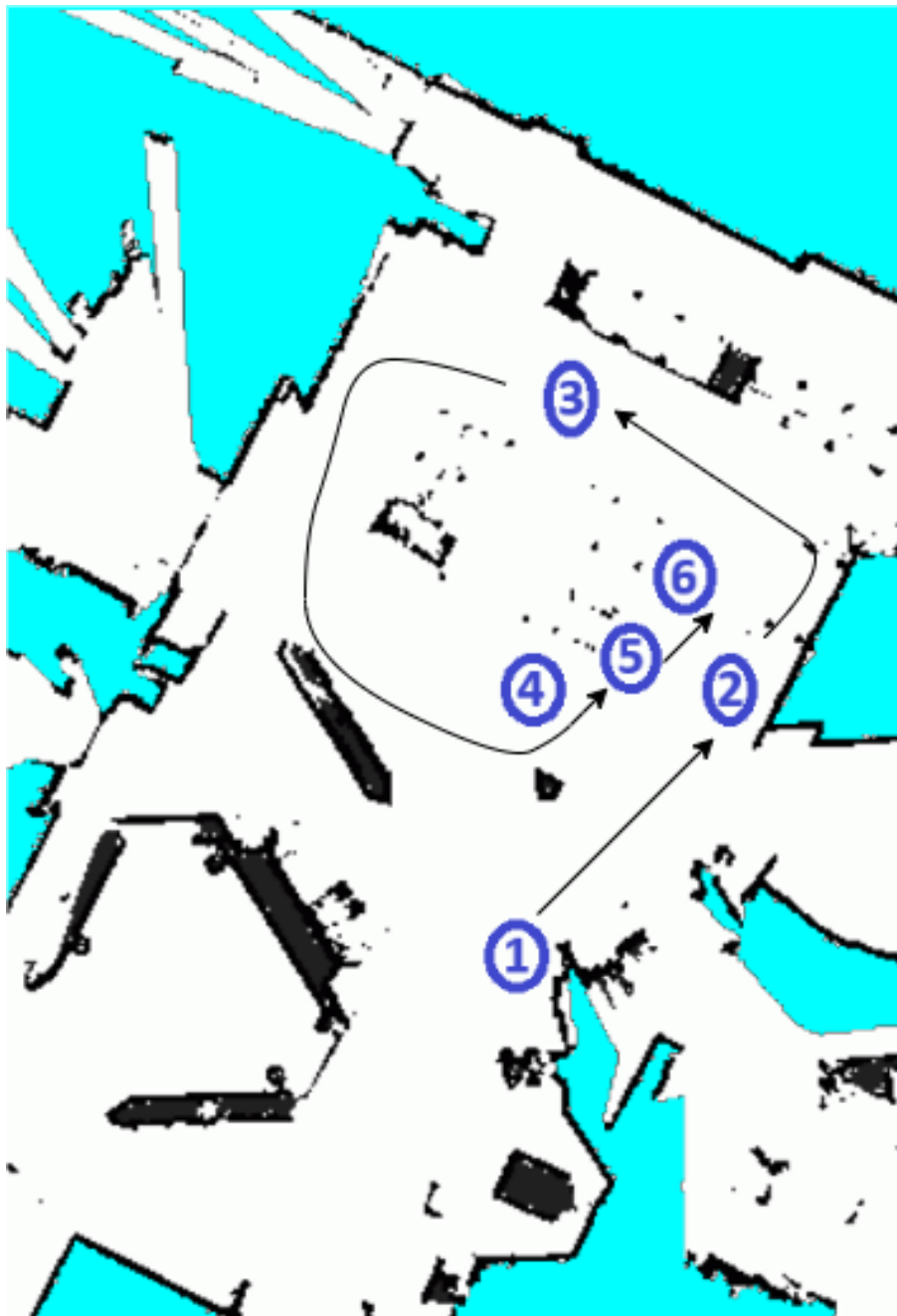


Figure 4.10: MiR100 Line Stocking route map.



(a) Docking flat shelf cart.



(b) Flat shelf carts waiting tray loading.



(c) Delivering workstations.

Figure 4.11: Different MiR100 positions during Line Stocking route.

The navigation paths of the MiR100 have been carefully planned so that the robot's movements never interfere with the working areas of the operators at the workstations. This guarantees uninterrupted human activity while the robot performs internal logistics.

Moreover, the MiR100 is equipped with a comprehensive suite of safety sensors, including LiDAR, ultrasonic detectors, and bumpers, as well as configurable emergency stop mechanisms. These features enable it to operate safely in dynamic environments shared with people, eliminating the need to physically isolate or reserve its movement areas. This collaborative design is key for agile production layouts and makes the solution ideal for integration in real industrial settings

4.3 Network Configuration

For this project, the existing laboratory Wi-Fi network, originally dedicated to the MiR100 robot, has been leveraged to connect all system components (see Figure 4.12). The MiR100 robot is assigned a fixed Internet Protocol (IP) address within this network to ensure reliable and consistent communication. Similarly, the Raspberry Pi units are connected to the same network, each receiving static or reserved IP addresses for stable identification and data exchange. This network architecture supports easy integration of future devices, facilitating system scalability and upgrades. The central control computer is also connected to this network, serving as the main hub for system management and coordination.

The Wi-Fi network is based on the IEEE 802.11ac (Wi-Fi 5) standard, offering theoretical maximum speeds up to 1.3 Gbps, operating primarily on the 5 GHz frequency band. This ensures high bandwidth and low latency, which are crucial for real-time data transmission and control in the logistics environment. The network access points provide sufficient coverage to encompass the FL, with robust signal strength and minimal interference.

The chosen wireless infrastructure balances mobility and reliability, allowing devices like the MiR robot and Raspberry Pi units to communicate seamlessly without the restrictions of wired connections, thus supporting dynamic reconfiguration and expansion of the automated logistics system.

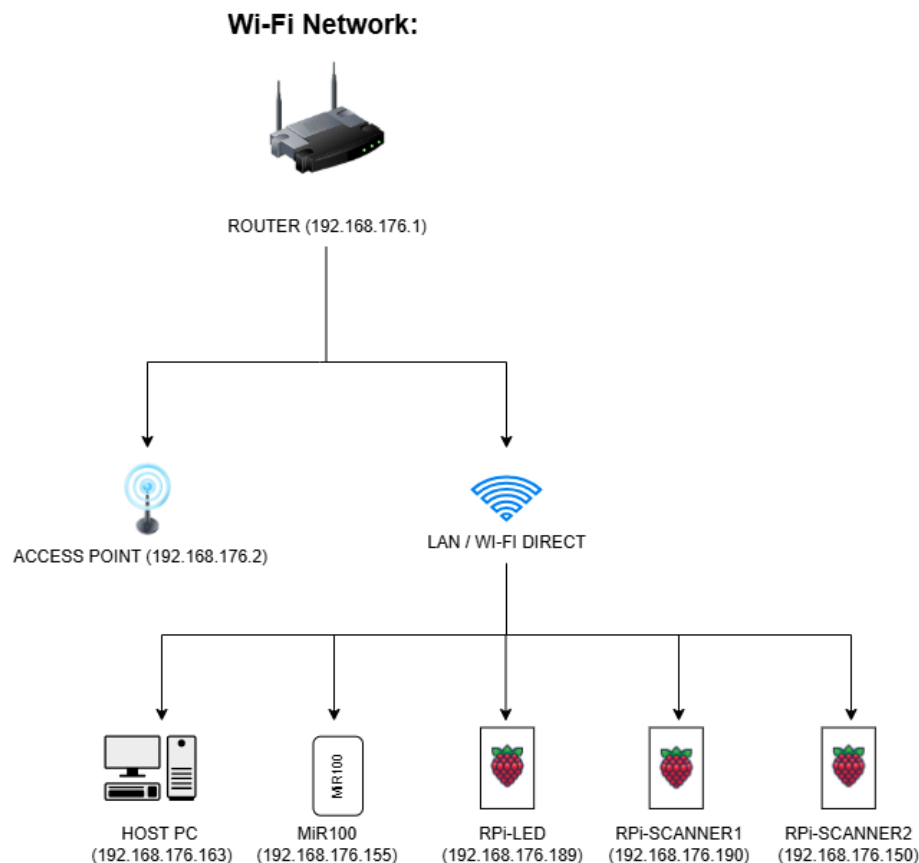


Figure 4.12: Network scheme.

4.4 Software Development

The software developed for this project was implemented using Streamlit, an open-source Python framework designed for building interactive web applications with minimal overhead. Streamlit allows rapid interface prototyping and seamless integration with Python logic, making it especially suitable for control panels and data-driven systems.

4.4.1 Control Software Development Approach

The development of the control software followed a modular and iterative approach, starting with the definition of system requirements and interaction logic between hardware components. The programming was carried out primarily in Python, due to its simplicity, flexibility, and strong support for networking, hardware interfaces, and rapid User Interface (UI) development through libraries such as Streamlit.

The system was designed to act as a central orchestrator, managing communication with various elements, including the MiR robot, Raspberry Pi controllers, the PLC, and user interface components. Each subsystem was initially tested in isolation and then gradually integrated into a single cohesive application.

One of the key architectural decisions was to implement a non-blocking, continuously refreshing execution model, which allows the software to remain responsive and up-to-date without halting ongoing processes [23]. This is particularly important to ensure that robot commands can be issued and executed independently, without disrupting or losing the state of the operational modes (e.g., kitting, line stocking). In other words, the application allows the MiR robot to be controlled in parallel with the active system modes, preserving system consistency at all times.

To maintain system state between refresh cycles, Streamlit's session-based global variables (`st.session_state`) were used. This enabled persistent data storage, safe interaction tracking, and dynamic UI updates, ensuring that no information is lost even as the page reloads automatically.

This structured development strategy facilitated early-stage testing, reduced the likelihood of communication errors, and enabled future extensions without major architectural changes.

4.4.2 Barcode Software

Each workstation includes a Raspberry Pi connected to a USB barcode scanner. The script running on the Raspberry Pi is responsible for:

- Waiting for barcode input from the operator.
- Sending the scanned code to the main control application over a TCP socket connection.
- Listening for confirmation responses from the server before becoming available for the next scan.

Although the code includes logic for controlling a status LED (for indicating activity or errors), this feature is currently not used in the physical implementation. The system operates in headless mode, meaning that the Raspberry Pi works entirely via network communication, with no visual feedback locally on the device.

This design allows for a clean and modular setup, where each Raspberry Pi acts as an independent input node for its associated workstation. By using standard socket communication, the system remains lightweight, responsive, and easy to replicate for additional stations.

4.4.3 LED Control Software

One of the Raspberry Pi 4 units is dedicated exclusively to the control of the Neopixel LED strips installed in the Factory Lab workstations. This device acts as the central visual signaling controller, responsible for receiving lighting instructions from the main application and reflecting the current system state through color-coded cues.

Upon startup, the Raspberry Pi initializes its LED configuration and enters a waiting state, continuously listening for incoming messages from the Streamlit server over a TCP socket. During this idle phase, it activates a test mode, temporarily illuminating all LED cells in orange to verify proper functionality and ensure the strips are correctly powered and detected. This startup effect also serves as a visual confirmation that the script has launched correctly.

Once the connection with the main server is established, the LED control module begins to process JSON-formatted instructions, which can contain three types of commands:

- **Initialization messages**, specifying how many LED strips (or “cells”) are connected and how many LEDs each one contains.
- **Update messages**, which assign specific colors to individual strips and define how many LEDs should be lit to reflect stock levels or tray requirements.
- **Clear messages**, which turn off all LEDs in the system.

The system supports a dynamic and flexible layout, allowing up to 8 strips with configurable lengths. Each strip can display a unique color and intensity depending on the workflow: for example, green for available, red for error, blue for completed orders, or directional animations to indicate pick order. These signals guide the warehouse operator during the replenishment process and help reduce human error.

In case of communication loss or unrecognized commands, the script includes fallback behavior to prevent misleading signals. It can automatically trigger a red alert state or return to standby mode to wait for the next valid message.

By isolating this logic on a separate Raspberry Pi, the visual signaling system remains responsive, modular, and independent, improving overall system reliability and maintainability.

4.4.4 User Interface and Interaction via Streamlit

The user interface developed for this project (see Figure 4.13) plays a central role in connecting all system components and enabling operator interaction. It was built using Streamlit, a Python-based web framework designed to create interactive dashboards and applications in a simple and intuitive way [24]. The interface runs locally on the main warehouse computer and provides an online view of the entire logistics system.

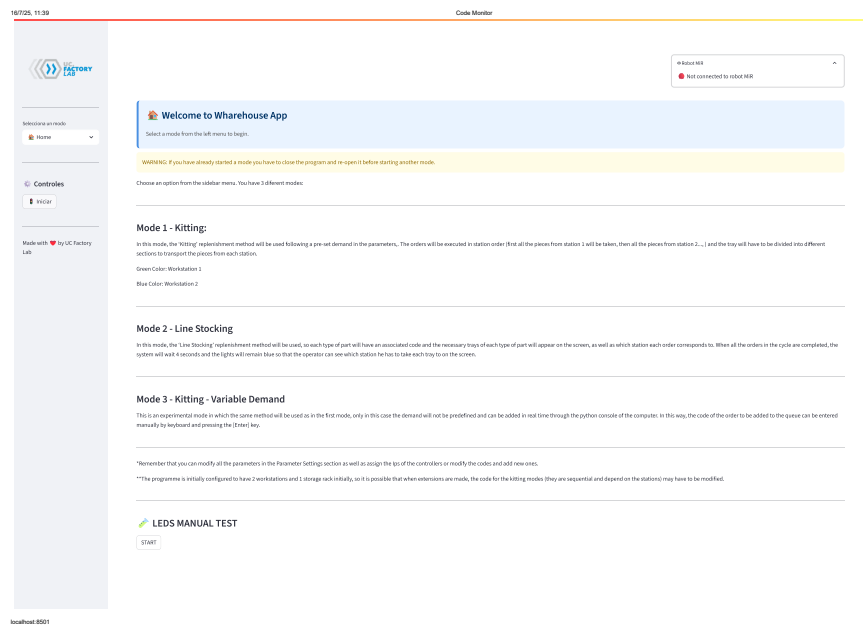


Figure 4.13: Home mode.

Through this interface, the operator can monitor active processes, visualize the status of each workstation, and respond to material replenishment requests. The design focuses on clarity and usability, with clearly defined sections for each operation mode (e.g., kitting, line stocking), as well as dynamic elements that update continuously to reflect system changes.

Interaction with the robot, Raspberry Pi devices, and the PLC is integrated into the interface via custom Python scripts and global state variables, allowing seamless communication across all components. This visual layer ensures that the operator can effectively supervise and manage the warehouse operations without needing to access low-level controls or configuration files.

Parameter Settings Mode

Parameter Settings mode is designed to allow users to configure all essential system parameters in a structured and intuitive manner through a tabbed interface developed in Streamlit (see Figure 4.14). This mode plays a crucial role in ensuring the application's flexibility and adaptability to various hardware configurations and workflows.

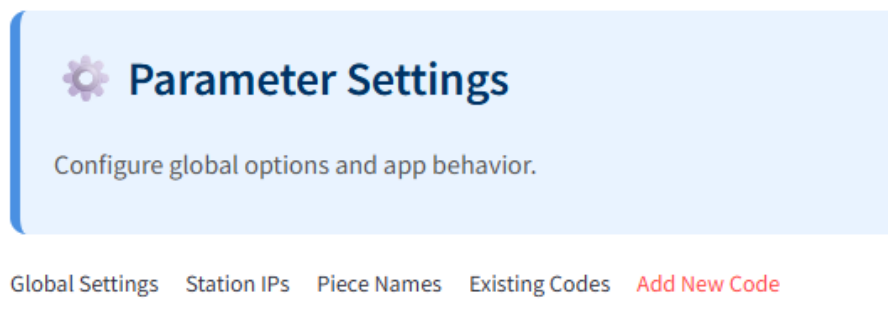


Figure 4.14: Initial panel.

The interface is divided into five main tabs:

- **Global Settings**

This tab allows the configuration of core system parameters (see Figure 4.15a), such as:

- Number of storage cells and shelves in the warehouse;
- Starting addresses for PLC communication;
- IP addresses of the PLC, Raspberry Pi (lighting controller), and the host PC;
- Communication port for the PC;
- Kitting piece sequence (used to determine the component delivery order);
- Number of containers per workstation in kitting mode.

All fields are editable, and changes are saved and immediately applied to the system upon confirmation.

- **Station IPs**

In this section, the operator can:

- View and modify the IPs and names of registered workstations;
- Delete or rename existing stations
- Add new workstation IPs and names.

This allows dynamic reconfiguration of the station mapping (see Figure 4.15b) without altering the codebase, and ensures correct routing of requests and data.

- **Piece Names and Images**

Each storage cell can be assigned a name and up to four reference images. These images assist operators in visually identifying the components during kitting or line stocking operations (see Figure 4.16a). Images are organized by views (e.g., top, front, side) and stored locally for quick access. This feature enhances usability and reduces picking errors.

- **Existing Codes**

This tab displays previously registered product codes (see Figure 4.16b). When a code is selected:

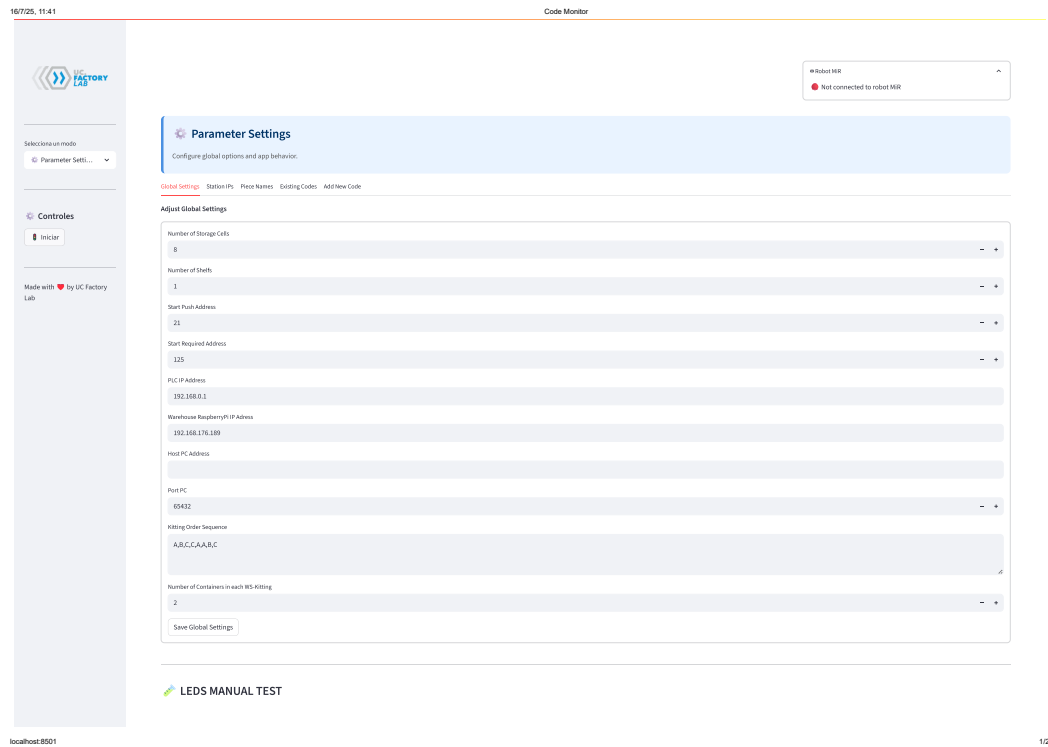
- The operator can rename it and assign it to a specific storage cell;
- Define the number of pieces required for Workstation 1 and Workstation 2;
- Visualize associated component images.

This section enables fast updates of existing assembly or replenishment codes, adapting to evolving production needs.

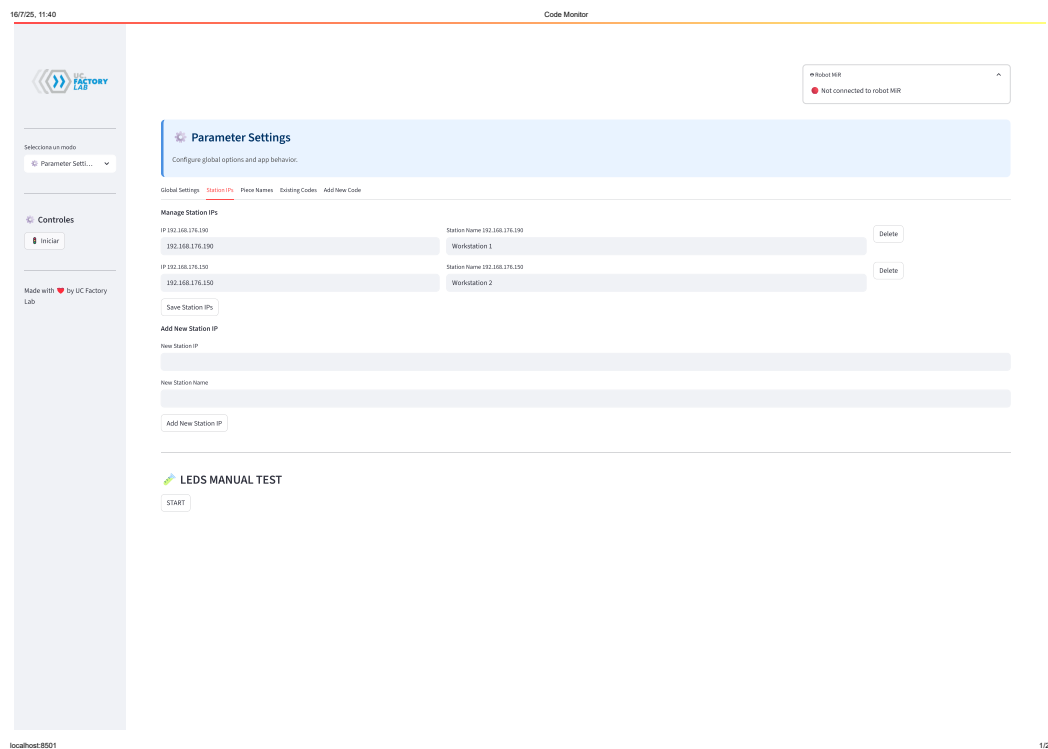
- **Add New Code**

Operators can register new product codes(see Figure 4.17) by:

- Assigning a code and name;
- Linking it to a storage cell;
- Specifying the required components for each workstation.
- Previewing component images as they are selected.

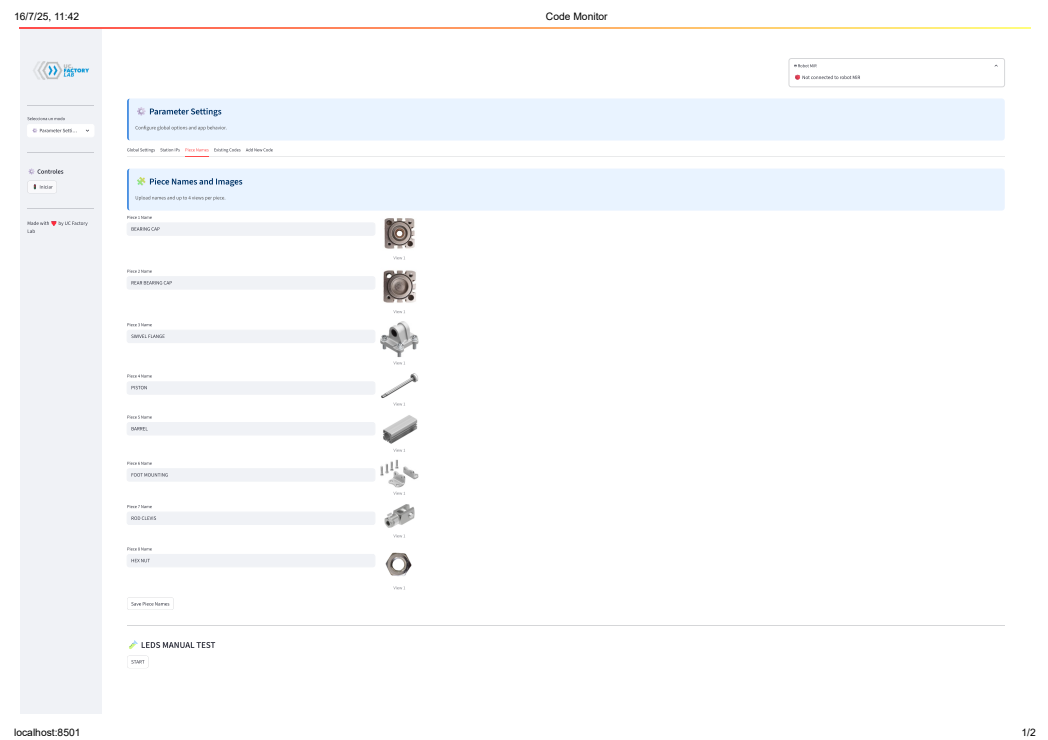


(a) Global settings GUI.

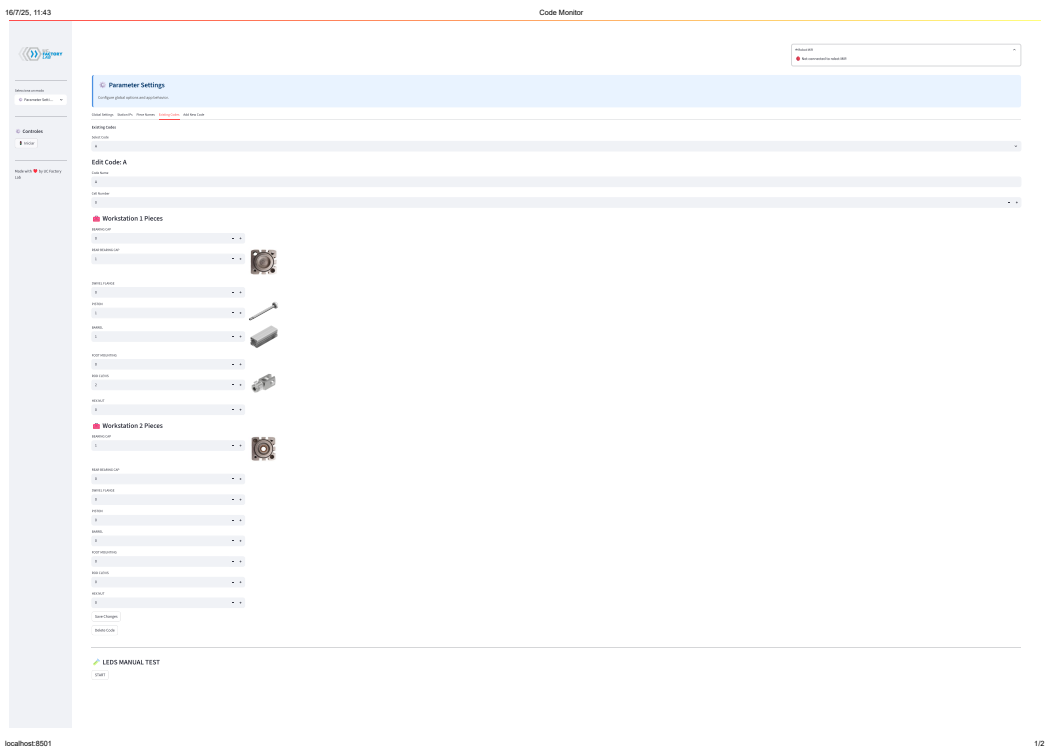


(b) Station IP GUI.

Figure 4.15: Different tab views.



(a) Piece names GUI.



(b) Existing codes GUI.

Figure 4.16: Different tab views(2).

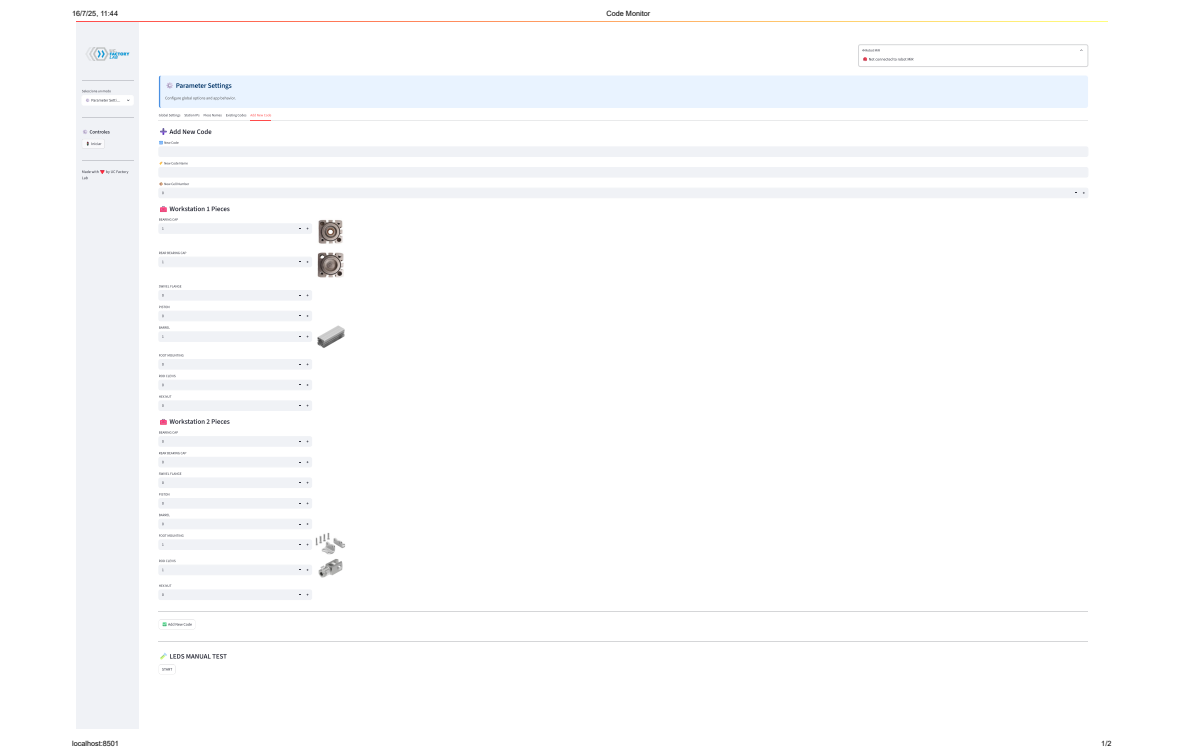


Figure 4.17: Add new codes GUI.

All these parameters are stored in a structured JSON configuration file, which is automatically loaded each time the application starts. Any updates made through the interface are written back to this file, ensuring that all custom settings persist across sessions without requiring manual configuration. JavaScript Object Notation (JSON) was chosen for its readability, ease of integration with Python, and widespread use in configuration storage due to its lightweight and human-readable format.

Kitting Mode

This mode implements a predefined, sequence-based kitting strategy, where the system ensures that a fixed number of kits are delivered to each workstation according to a configured logic. The application uses a continuous auto-refresh mechanism to maintain real-time status without requiring user interaction, ensuring the interface updates container counts and order status dynamically.

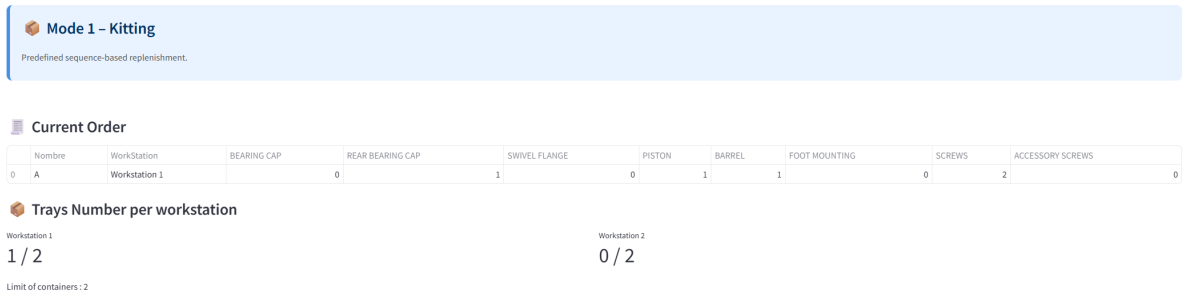


Figure 4.18: Kitting GUI.

At the beginning of the kitting cycle, the warehouse operator receives the demand

sequence, which defines the type and number of pieces required to assemble each kit for the corresponding workstations (see Figure 4.18). In this project, a randomized sequence was used to simulate a realistic but controlled scenario.

The demand is displayed clearly on the screen, allowing the operator to identify the specific components and quantities that need to be picked from the storage rack. This ensures that each kit is correctly composed before being delivered by the mobile robot. The system provides a visual interface that dynamically reflects this information, minimizing errors and streamlining the manual picking process.

Once the demand is received, the warehouse operator must press the physical buttons corresponding to the components indicated by the system. Each button is associated with a specific piece and triggers a validation process. If the selected piece matches the expected one, the system confirms the action with a success message; otherwise, an error message is shown to alert the operator (see Figure 4.19). These buttons are connected to a Pick-to-Light system that guides the selection process visually.

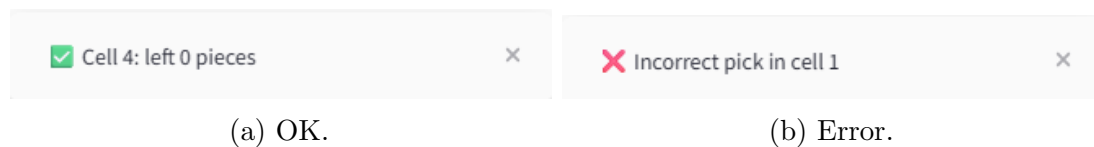
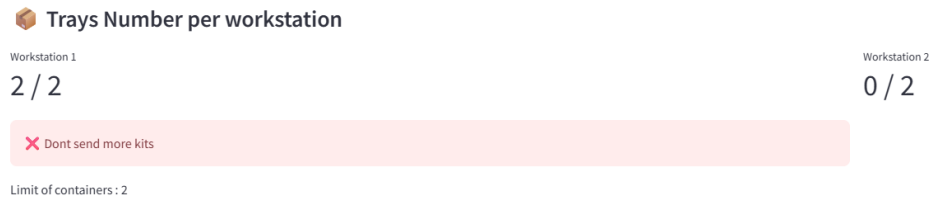


Figure 4.19: Guide messages.

This mechanism ensures that only the correct components are picked. Once all required pieces for the current subassembly are confirmed, the system automatically updates and displays the next set of pieces needed to complete the full kit. This step-by-step guidance improves accuracy and aligns the operator's workflow with the digital demand sequence.

The system also keeps track of the movement of kits across workstations. This means that as soon as a kit arrives at Workstation 1, the interface registers it as "received" by that station. Once the operator at Workstation 1 confirms that the assembly task is completed—by scanning any barcode—the tray is automatically reassigned to Workstation 2, freeing up the slot at Workstation 1 (see Figure 4.20b).

When any workstation reaches the maximum number of allowed trays, the system automatically pauses further demand for that station and issues a notification to the warehouse operator (see Figure 4.20a), preventing system overload and ensuring smooth logistics flow.

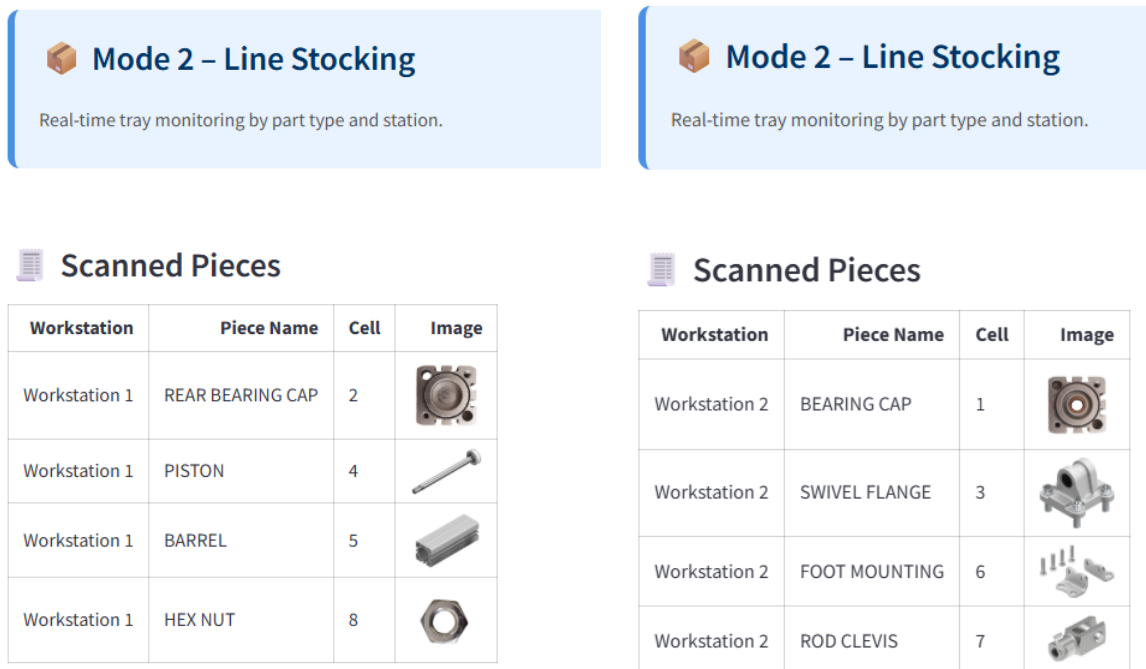


(a) Limit of trays.



(b) Normal flow.

Figure 4.20: Monitoring of tray positions over the workstations.



(a) First delivery WS1.

(b) First delivery WS2.

Figure 4.21: Pre-Deliveries defined by the warehouse operator.

Line Stocking Mode

Line Stocking is a replenishment method based on demand generated directly by operators at the workstations. Unlike Kitting, where predefined kits are assembled and sent, Line Stocking aims to keep specific components continuously supplied, depending on the needs of each station.

At the beginning of the process, the control operator defines how many trays will be sent to each workstation. In our simulation, we have used one tray per type of piece, each with enough pieces to assemble three products—one of each type (see Figure 4.21). This distribution is defined based on the real production demand. Once the mode is activated, the warehouse operator is presented with this predefined information on screen. For each item, the interface displays the part number, the target workstation, and a reference image of the component to simplify picking. It is also essential that each workstation has a printed or digital list of its own demand, so operators know which sub-assemblies they are responsible for.

During the operation of the production line, the demand list continues to grow. At some point, a workstation may run out of a specific component. In that case, the station operator is required to scan the barcode associated with the empty tray. This triggers a replenishment request, which is received by the warehouse operator via the central interface. To complete the restocking task, the warehouse operator must press the buttons corresponding to the storage locations of the required components. These buttons are connected to a Pick-to-Light system that guides the selection process visually (see Figure 4.22).

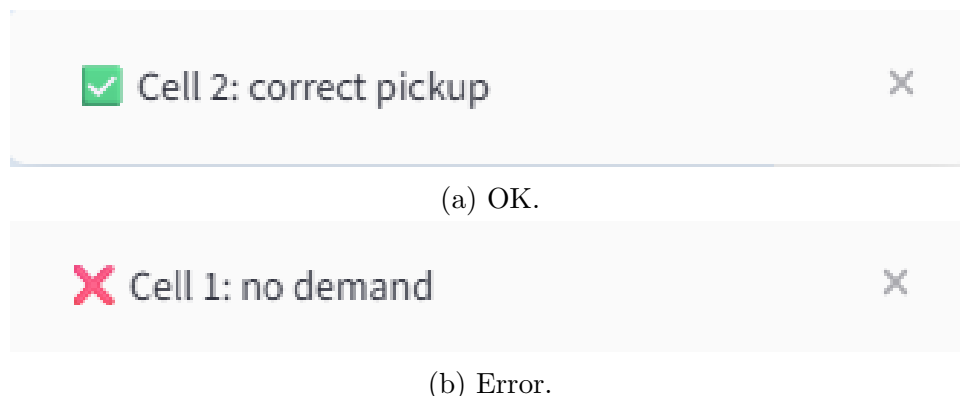


Figure 4.22: Validation messages shown during restocking process.

It is crucial to note that if the station operator accidentally scans a code not assigned to their workstation, the system detects the mismatch and sends an alert to the central warehouse operator. This enables immediate detection and correction of operational errors, improving the system's robustness and responsiveness.

Finally, once the products have been fully assembled, the warehouse operator is also responsible for collecting the completed units from the workstations. This step is carried out in coordination with the return of empty trays, ensuring a continuous flow of components and finished goods throughout the system.

MiR100 Interface

Located at the top right corner of the interface, the robot control panel is designed as a persistent dropdown menu, accessible at all times regardless of the operational mode.

This design ensures seamless and continuous interaction with the robot during the entire production workflow.

The interface prominently displays the robot's current connection status (see Figure 4.23), providing real-time feedback on whether the system is successfully linked to the robot. Once a connection is established, the operator can activate the robot's "play" mode through a dedicated control button, allowing the robot to start executing predefined missions autonomously.

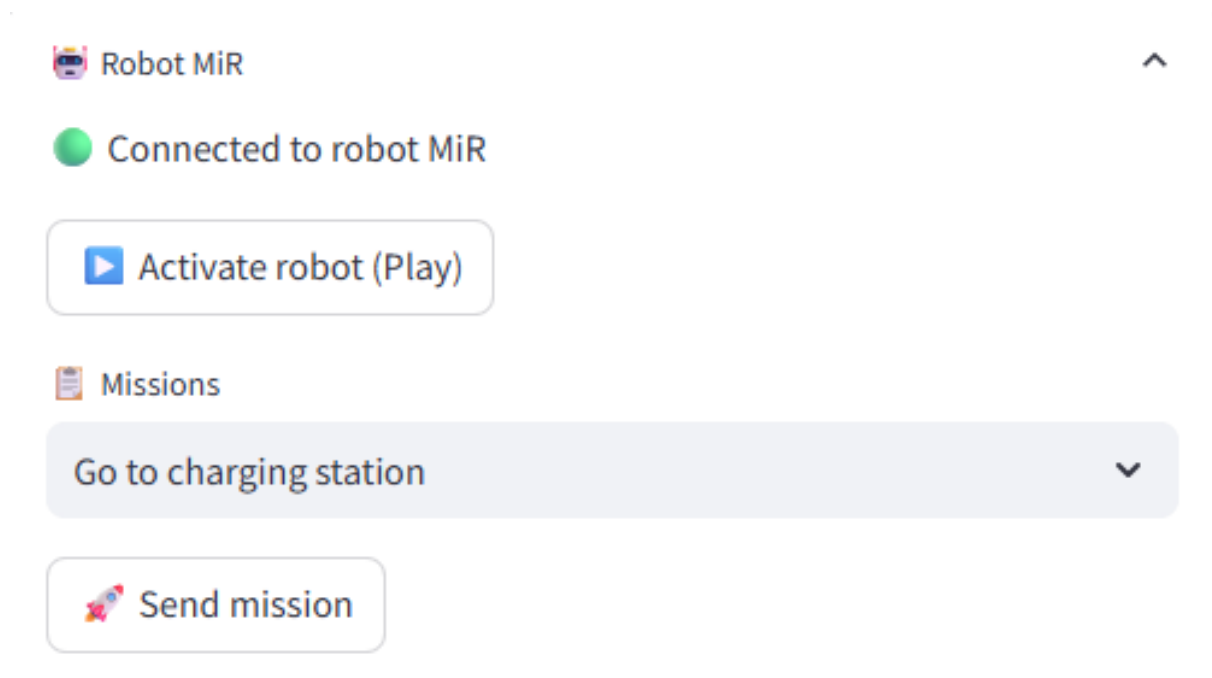


Figure 4.23: Robot GUI.

One of the key features of this interface is its ability to dynamically retrieve and display the robot's mission list. These missions are presented in an easy-to-navigate dropdown menu (see Figure 4.24), enabling quick selection and dispatch of tasks. The system's modular design permits straightforward addition or modification of missions, supporting future scalability and customization without requiring significant changes to the interface or backend.

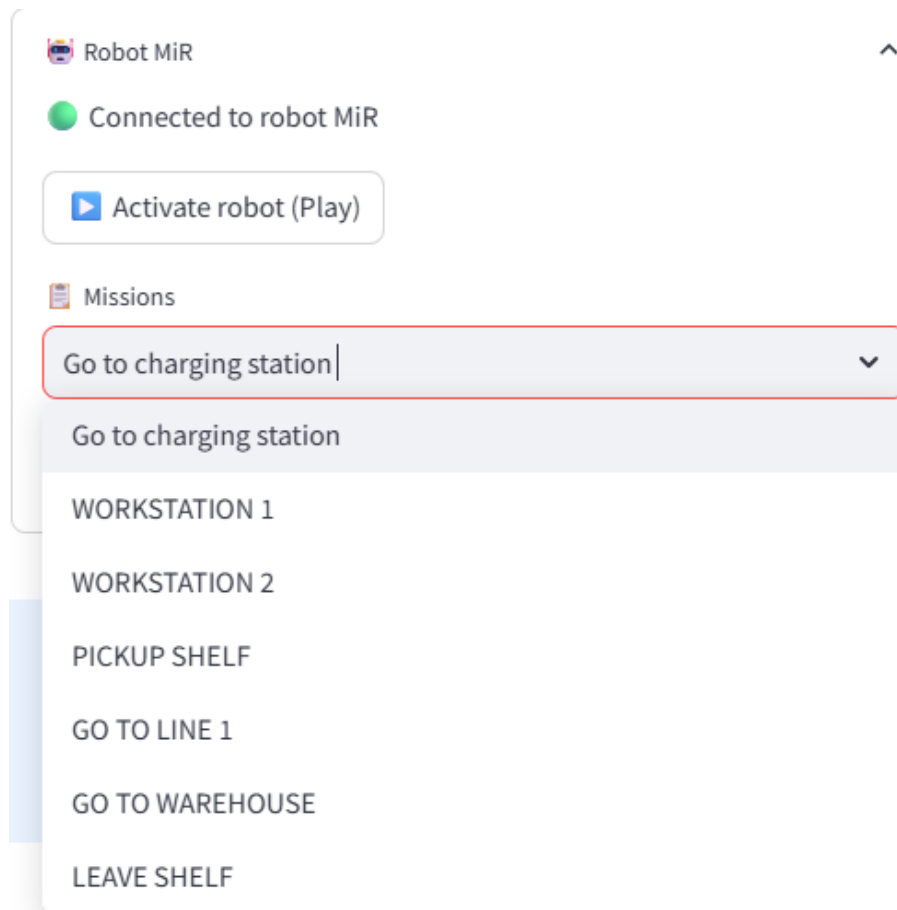


Figure 4.24: Robot mission list GUI.

Overall, this robot interface provides an intuitive and efficient way to monitor and control the mobile robot, integrating it seamlessly into the production environment and enhancing the flexibility and automation capabilities of the system.

4.5 Custom Components for Physical Integration

As part of the system implementation, various custom mechanical components were designed and fabricated to improve the physical integration, safety, and visual clarity of the Factory Lab setup. These parts were modeled using Autodesk Fusion 360 and manufactured using Fused Deposition Modeling (FDM) 3D printing technology. [25]

The use of 3D printing enabled rapid prototyping and low-cost customization, allowing for precise adaptation to the dimensions of existing racks, carts, and electronic modules. Each component was designed with a specific purpose: to improve cable management, facilitate operator interaction, or protect sensitive hardware.

4.5.1 Aesthetic and Functional Enhancements to the Rack

The original state of the rack presented several limitations in terms of appearance and industrial viability. All cables were exposed, and the LED strips were directly adhered to the surface of the structure. This approach, while functional for demonstration purposes, lacked the robustness and professional finish expected in a real industrial environment.

To address this issue, a series of custom components were developed to visually and functionally improve the rack. The main goal was to conceal and protect all visible wiring while integrating the LEDs in a more structured and accessible way.

The design process began by accessing the official 3D catalog provided by ITEM, the manufacturer of most of the structural elements used in the Factory Lab, including the rack in question. From this catalog, we obtained the digital 3D model of the rack profile, which served as a reference for designing custom components that would fit perfectly with the aluminum bars used in the structure.

The first element created was a cover piece that replicates the geometry of the vertical lateral bars (see Figure 4.25). This piece acts as a bridge between the vertical and horizontal elements of the rack's frame. To complement the protection on the sides, we also integrated a commercial rubber bar provided by ITEM, which fits perfectly along the same profiles. This rubber element enhances the shock resistance and overall finish of the assembly and is fully compatible with both the original rack structure and the 3D-printed cover.

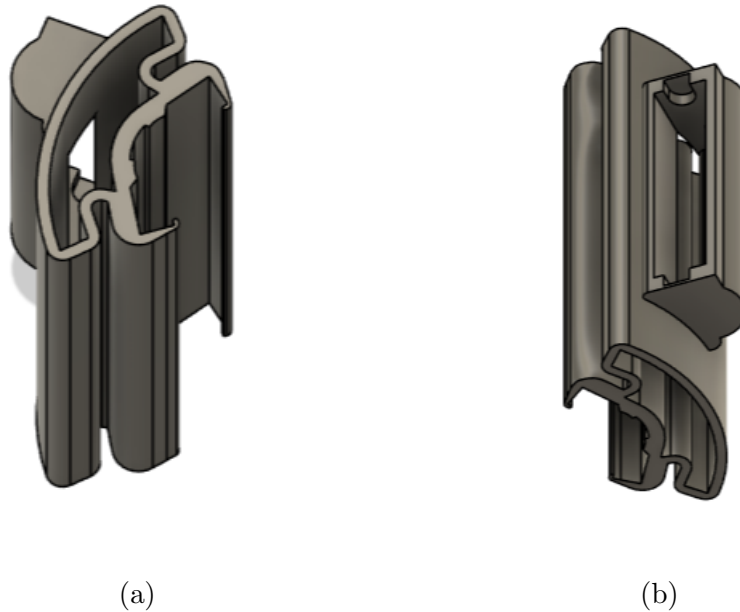


Figure 4.25: Different views of the bridge piece.

To complete the front of the rack in a functional and visually coherent way, a set of horizontal rectangular tubes was designed to act as the main structural connection between the side covers and the button enclosures.

These rectangular tubes continue across the front of the rack, forming a chain of interconnections. From the initial bridge piece, a tube connects to the first button box, then from that box to the next box, and finally to the opposite bridge on the other side. Each button enclosure has lateral connectors that use the same interlocking system, allowing all elements to be joined in sequence. This configuration results in a continuous, modular, and mechanically stable front panel. Each rectangular tube includes a longitudinal opening precisely dimensioned to allow the insertion of the Neopixel LED strips along with their protective plastic sleeve. This design ensures that the LEDs remain fully enclosed and shielded from external impacts, dust, or accidental contact, while

maintaining high visibility from the front. The opening allows the light to diffuse outward cleanly, resulting in a professional and polished appearance, which is far more suitable for industrial environments than surface-mounted, unprotected strips.

To ensure secure mounting of the button enclosures (see Figure 4.26) to the front of the rack, a custom-designed bracket was developed to interface directly with the horizontal rectangular tube. This bracket fits snugly against the rear side of the tube and includes two precisely placed holes to accommodate standard screws. The rear face of each button box is designed to match the geometry of this bracket, allowing for a direct and aligned screw connection between both parts. When assembled, the bracket acts as an intermediate support, transferring the mechanical load from the button enclosure to the structure of the rack. This ensures that the enclosures remain firmly fixed during operation, while also allowing for quick removal or replacement if necessary.

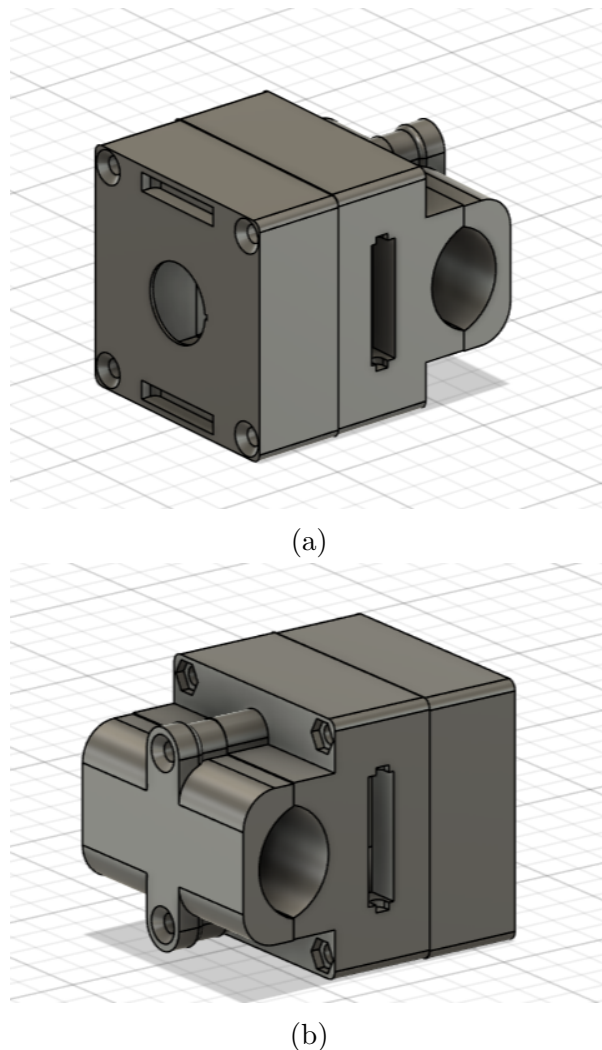


Figure 4.26: Different views of the complete box.

The integration of all these custom components has resulted in a fully enclosed, modular, and industrial-grade front panel for the rack. Thanks to the combination of 3D-printed pieces, compatible commercial elements from ITEM, and a functional design tailored to the Factory Lab environment, the solution achieves a significant improvement in both safety and aesthetics. All cables are now hidden, the LEDs are fully protected

and integrated into the structure, and the operator interface is cleanly laid out through the front-mounted button enclosures.

This final configuration not only meets ergonomic and visual standards, but also reinforces the modular and professional character of the system. The following image shows the final assembled rack, with all components installed and functioning as part of the complete solution.

4.5.2 Protective Enclosures for Raspberry Pi Units

As previously discussed, Raspberry Pi boards are not originally designed for industrial environments, and thus require additional protection to ensure their long-term reliability under real working conditions. One of the main concerns in this context is the exposure to dust and mechanical stress, especially when the devices operate for extended periods. Another important factor is temperature control, as prolonged usage can lead to excessive heat buildup and potential damage to the board.

An initial 3D-printed case was already available in the lab, but this design proved unsuitable for the project. Its top section was too exposed, allowing dust and particles to accumulate inside the enclosure. Additionally, it lacked internal mounting features, meaning the Raspberry Pi board could not be properly secured, making the setup unstable and unsafe.

The final solution was to design a custom protective enclosure, inspired by the original one but significantly improved (see Figure 4.27). The new case features a more enclosed upper section to block contaminants, while still offering passive ventilation through lateral slits to allow airflow and prevent overheating. The top also includes targeted openings to access the GPIO pins, enabling the use of expansion modules or wiring when needed.

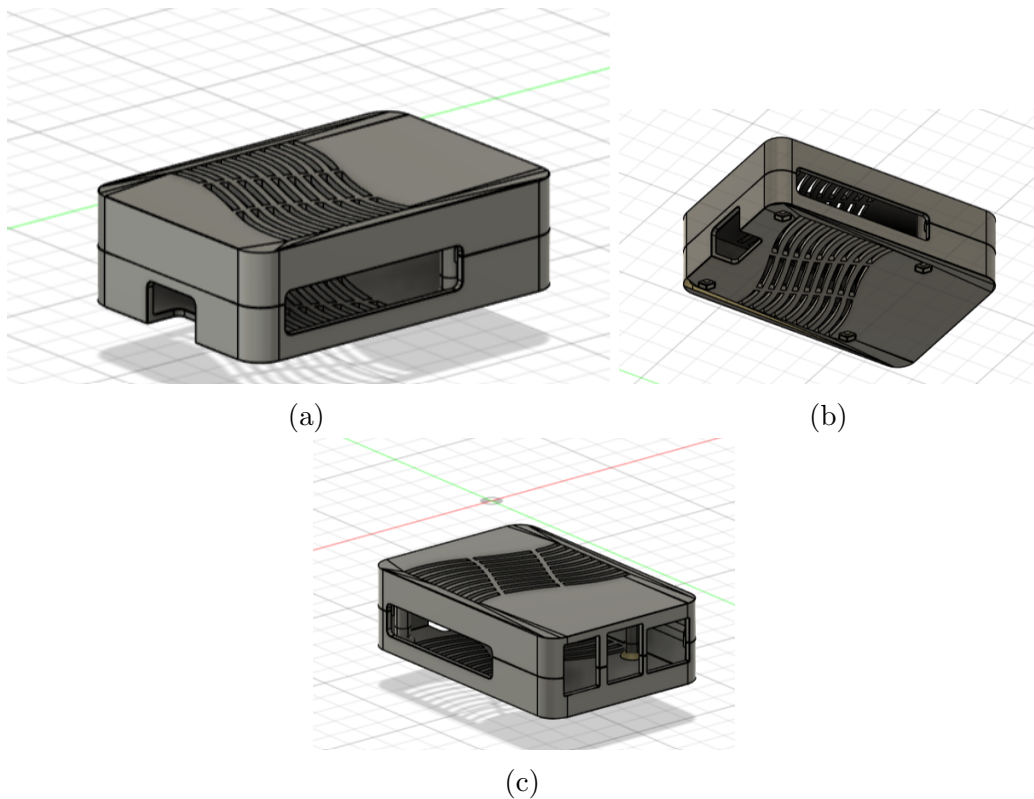


Figure 4.27: Different views of the new box created.

Crucially, the design incorporates internal fastening points so that the Raspberry Pi can be screwed securely into the enclosure.

4.6 Functional Tests and Results

4.6.1 Software Validation

In this first phase, the correct operation of the control software, developed in Streamlit, was evaluated, as well as its integration with the system components. The following key aspects were verified:

- **Socket connection:** The connection between the central system and the various devices (such as the PLC and Raspberry Pi) was successfully established when each operating mode was activated. Although there is sometimes a short delay when initiating the connection, it stabilizes within a few seconds and performs reliably throughout the session.
- **Global parameter configuration:** The system allows the user to easily modify the main parameters (such as IP addresses, number of trays, replenishment sequences, etc.) from the Parameter Settings section. All parameters are stored in a JSON file, making them persistent and editable without altering the source code. The system also associates images with each part type. To update or add images, the user only needs to place .png files into the images directory of the project using the format: PartName_1.png, PartName_2.png, up to 4 views per part. This design allows easy visual customization without needing to restart the application.
- **Real-time display updates:** Thanks to the built-in auto-refresh mechanism, changes to files (images or parameters) are displayed on-screen within seconds, eliminating the need for manual resets or restarts.

Additionally, a dedicated LED test mode has been added. This feature allows developers to check the LED system independently, without needing to connect to the PLC or the robot. When activated, it turns the LEDs yellow (see Figure 4.28) and makes them blink for a few seconds, providing a quick and visual hardware check.



Figure 4.28: LEDs testing.

4.6.2 Validation of the Pick-to-Light and Push-Button System

A fundamental aspect of the system is the physical interaction between the operator and the components, particularly the Pick-to-Light mechanism and push-buttons integrated into each storage cell.

- **Automatic LED activation based on demand:** When a picking or replenishment order is generated, the system automatically lights up the corresponding LEDs, visually guiding the operator to the correct cell.
- **Validation through physical buttons:** When an operator presses a button, the system checks whether the action matches an active demand. If correct, the LED turns off and the demand is marked as completed. If incorrect, a red light is triggered and an error message is shown to alert the supervisor.

- **Error prevention and feedback:** Tests were conducted by deliberately pressing incorrect buttons or scanning the wrong barcodes. The system properly detected these cases, triggered the red LED, and reported the issue to the main operator in real time.
- **Efficient real-time interface:** Thanks to Streamlit’s Autoresfresh, the interface updates itself periodically without requiring manual reloads. This eliminates the need for multithreading, which can be heavy and hard to debug, especially in long-running applications. The result is a lightweight, responsive, and more robust interface capable of operating continuously without degradation.

4.6.3 Validation of MiR100

One of the final stages of testing involved verifying the correct integration of the MiR100 mobile robot with the rest of the system. The process requires a series of manual and automatic steps to ensure smooth mission execution:

- **Physical activation:** The robot must first be manually powered on using its physical power button. Once started, the display panel allows the user to change the robot’s state to “Play”, activating it and enabling remote control.
- **Connection and readiness:** After switching to Play mode, the robot changes its LED color to green, indicating that it is online and ready to receive instructions from the control software.
- **Mission list availability:** The robot’s mission list—configured via the MiR interface—was successfully loaded and remained accessible during all testing. The system was able to send missions from within both operational modes (Kitting and Line Stocking) without conflicts or delays.

This validation confirms that the MiR100 can be used seamlessly as part of the overall workflow, reliably handling transportation tasks triggered by the operator or system status.

4.6.4 Final Results

After completing the hardware integration, software deployment, and structural improvements described in the previous chapters, the final stage of the project consisted of assembling and testing the full physical system within the Factory Lab environment.

This chapter presents a visual summary of the completed implementation, focusing on the physical aspects of the solution: the modified rack with integrated lighting and button systems, the mobile robot in action during material delivery cycles, and the installation of electronic components such as Raspberry Pi units with their protective cases.

All the elements were designed to operate online and under realistic conditions, allowing for a smooth and safe interaction between operators, automated systems, and mobile robotics. The following images illustrate the final state of the system as deployed in the lab (see Figure 4.29 and Figure 4.30)

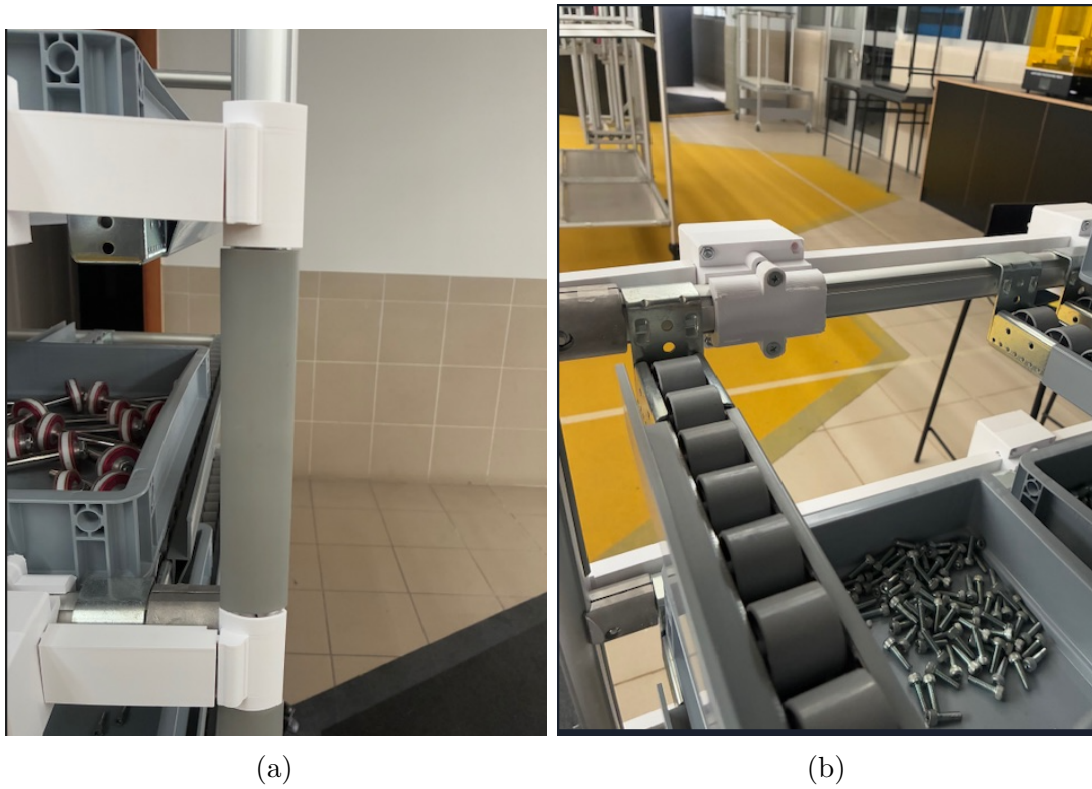


Figure 4.29: Different views of the finished rack.

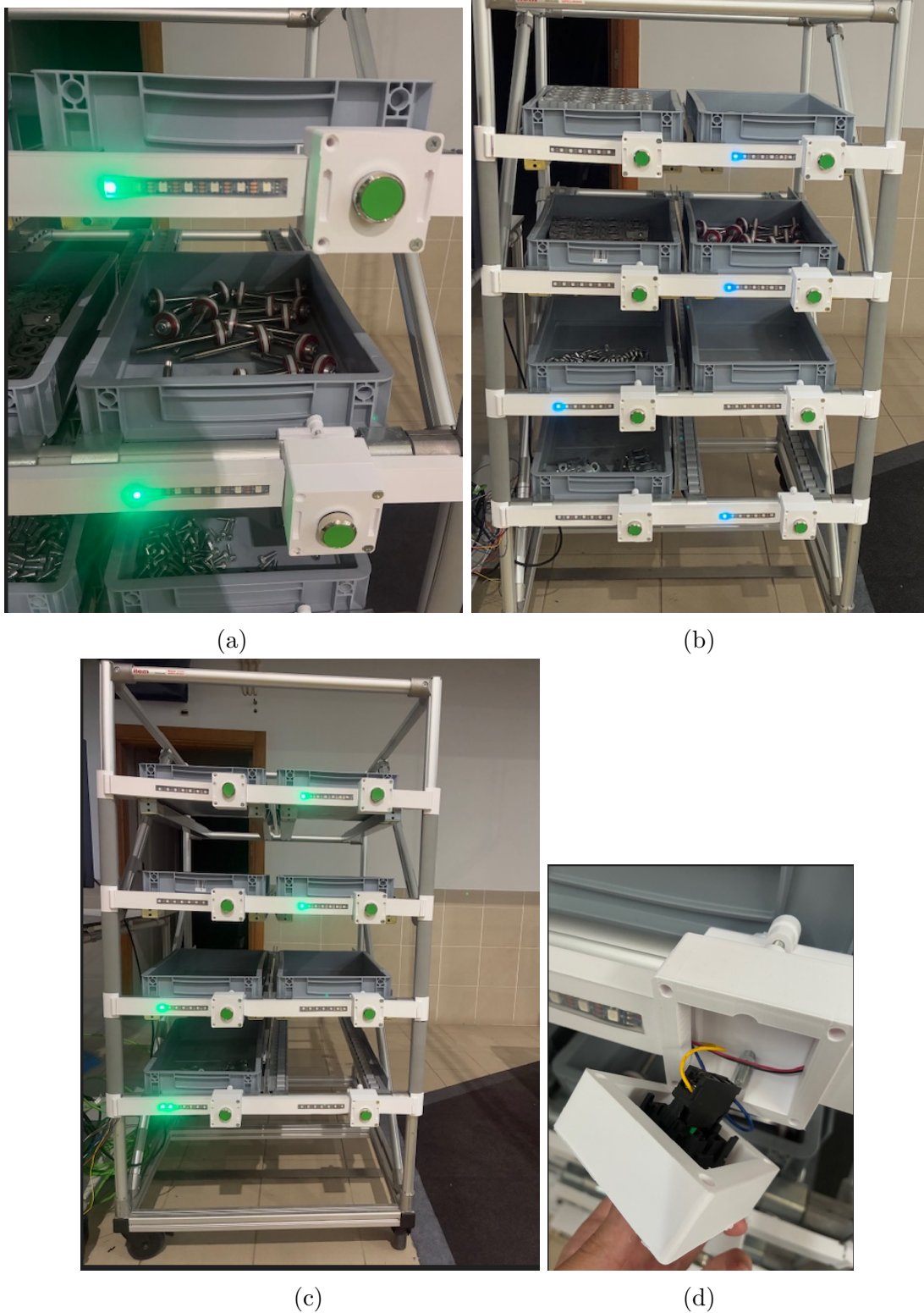


Figure 4.30: Pick to Light system results.

A comparison between the initial Raspberry Pi case design (see Figure 4.31) and the final improved enclosure highlights the evolution of the solution. The original case featured a highly exposed top surface, offering minimal protection against dust and external elements. It also lacked internal fixing points, which meant the Raspberry Pi board remained loose inside the case, compromising stability and safety. In contrast, the

final version includes a partially enclosed top, lateral passive ventilation slits.

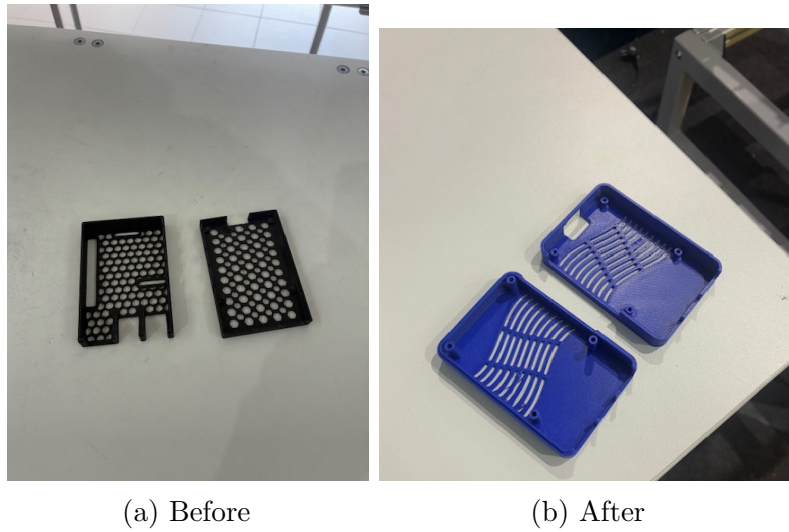


Figure 4.31: Comparison between Raspberry Pi boxes.

The final enclosures were printed, assembled, and fitted with the corresponding Raspberry Pi units, fully wired and ready for deployment (see Figure 4.32). Each case houses the board securely, with access to the required ports and GPIO pins for barcode readers or LED control systems.

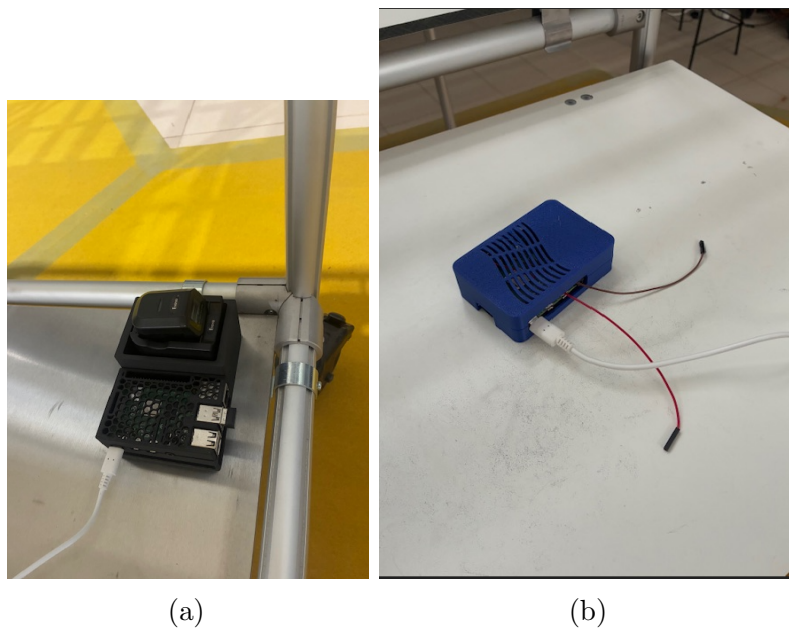


Figure 4.32: Final view of the assembled Raspberry Pi units inside their protective enclosures, mounted and ready for use in the system.

Chapter 5

Conclusions and Future Work

5.1 Discussion

The development of this system contributes to automation of intralogistics operations in an industrial environment. Throughout this project, we have designed and implemented a complete system capable of managing material flows between storage areas and production lines, supporting both kitting and line stocking strategies. The result is a scalable and modular solution that combines hardware and software in a cohesive, robust architecture.

From a software perspective, the use of Python with Streamlit has provided a powerful and intuitive interface, allowing operators to interact with the system easily. The implementation of multiple modes (Parameter Settings, Kitting Mode, Line Stocking Mode, etc) provides flexibility and adaptability to different production needs. In addition, features like real-time updates via Autorefresh, and dynamic parameter configuration make the system user-friendly and highly functional.

Hardware-wise, the integration of Raspberry Pi boards, Neopixel LED strips, and push buttons has enabled the implementation of an effective Pick-to-Light system, guiding operators through each picking and replenishment task. The decision to include a test mode for the LEDs has proven to be very useful for verifying functionality without the need to start a full PLC-robot cycle, adding reliability during setup and maintenance. The communication between different devices, especially the use of sockets to exchange information with the PLC and the robot, has shown to be stable and consistent despite initial delays during mode initialization. Once connections are established, the system operates smoothly, reacting in real time to demands, button presses, and replenishment needs.

One of the most remarkable achievements is the integration with the MiR robot. The ability to automatically trigger missions and track kit movement between stations brings a realistic industrial context to the system, simulating real intralogistics workflows. This, combined with the feedback and control loops implemented through barcode scanning, enhances traceability and coordination among operators and systems. Throughout the development, we also considered ergonomics and usability. The placement of Raspberry Pis, LEDs, and buttons was carefully planned to ensure accessibility for operators. Additionally, the inclusion of visual feedback in the interface improves clarity, reducing errors and training time.

Beyond its technical achievements, one of the most valuable outcomes of this project has been the successful deployment of the system in the Lean Manufacturing Room of the Factory Lab. This environment simulates real industrial workflows and now

hosts a fully functional version of the system, offering students and future engineers the opportunity to interact with real-world concepts such as kitting, line stocking, Pick-to-Light systems, and mobile robotics. Thanks to the system's modularity and intuitive interface, students can not only understand theoretical principles but also experiment with socket communication, PLC-Raspberry Pi integration, mission-based robot operation, and human-machine interaction. This hands-on learning tool transforms the Factory Lab into a dynamic teaching space, reinforcing concepts of Lean Manufacturing, Industry 4.0, and collaborative automation in a tangible, impactful way.

5.2 Improvement and Expansion Opportunities

The modular and flexible architecture of the developed system allows for easy adaptation to a wide variety of industrial configurations. The capability to manage different types of parts, workstations, and operating modes ensures that the system can scale and adjust to the specific needs of diverse production environments without requiring complete redesigns.

Furthermore, the integration of the MiR mobile robot adds an additional layer of versatility, as its mobility and mission-based system allow for rapid reconfiguration of the physical layout or extension of the solution to new production areas or warehouses. This approach facilitates deployment in industrial plants with multiple work zones or variable workflows, responding effectively to changing production and logistics demands. Thanks to this flexibility, the system is not only valuable for the current Factory Lab setup but also paves the way for future expansions in real industrial environments, where the ability to adapt to new products, assembly lines, and requirements is key to maintaining competitiveness and efficiency.

One significant enhancement we were unable to implement due to logistical and economic constraints is the integration of RFID technology. Incorporating RFID systems could greatly improve traceability, speed, and accuracy in identifying parts and kits throughout the production process. This technology would reduce the need for manual scanning and minimize human errors, streamlining inventory management and real-time monitoring. Another promising improvement is the addition of a digital tablet display for operators. This would provide greater flexibility and ease of use, allowing operators to interact more intuitively with the system while moving freely around their workstations. The implementation of such a device is straightforward and could substantially enhance operator experience and productivity.

Looking further ahead, a more ambitious development would be the integration of robotic arms at the assembly stations themselves. These robots could automate specific assembly tasks, increasing precision, reducing cycle times, and alleviating repetitive manual work for operators. Although this represents a challenging step in terms of complexity and investment, it points toward the future of fully automated, smart production lines.

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Appendix A

3D BLUEPRINTS

