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Enhancing Manufacturing Flexibility Through Automation Packaged Solution (APS): A Case Study Approach

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Abstract. The use of automation is reshaping tasks in diverse industries, leading to increased productivity and efficiency. The manufacturing sector, in particular, has enjoyed significant advantages from automation, including enhanced quality control, waste reduction, and improved worker safety. However, while the advantages of automation in manufacturing are clear, the implementation of automation in complex manufacturing processes is not without its challenges. One such challenge is ensuring adaptability to new products. In addition, the initial investment for automation in manufacturing processes often presents a significant financial difficulty, particularly in the areas of engineering, design, and programming. The aim of this paper is to provide flexible solutions that can be adopted on any manufacturing line within a short timeframe. This type of flexible solution is referred to as Automation Packaged Solution (APS). APSs involve the deployment of robotic systems and vision technologies to automate specific tasks. The key advantage of these flexible solutions is their ability to adapt to the introduction of new products into the production line without the need for extensive reengineering and reprogramming. The approach involves designing detailed computer simulations based on the initial solutions and bringing the solution to life through an offline commissioning method. In this research, a case study was conducted at a manufacturing plant in Sweden, where two APSs were introduced to their assembly line: Precise screwing and accurate application of product labeling. These APSs play a crucial role in facilitating rapid upgrades and adjustments to automation systems, especially considering the diverse range of product models. This adaptability reduces the time and resources required for reconfiguration and contributes to enhanced operational efficiency, cost-effectiveness, and more sustainable manufacturing solutions. Moreover, it opens up the possibility of transferring these APSs to another production line if the need arises.

Keywords. Automation, Flexibility, Industrial Robots, Manufacturing

1. Introduction

Flexible Manufacturing System (FMS) has become a critical focus in the field of industrial automation [1]. The ability to quickly adapt to changing market demands and accommodate variations in product volume and mix is essential especially in the era of Industry 4.0 [2],[3]. Automation plays a central role in enhancing manufacturing flexibility [4] and has been widely adopted in various industries, offering benefits such as increased productivity, improved product quality, and enhanced worker safety [5]. This transformation in manufacturing processes has been influential in driving efficiency and sustainability, leading to higher customer satisfaction and brand reputation [6].

Although we acknowledge the advantages of automation, the smooth integration of automation into manufacturing processes comes with its own challenges. One of the primary obstacles is the demand for flexibility, particularly the ability to quickly adjust to the production of new and diverse product lines [7]. Moreover, the substantial initial investment necessary for automating manufacturing processes represents a financial obstacle, especially within the domains of engineering, design, and programming [8]. In response to these challenges, researchers have been exploring innovative approaches to respond to these complexities.

In the field of manufacturing system design, decision-makers have the opportunity to plan for adaptability right from the start. Over the past few decades, a lot of research has focused on designing manufacturing systems for different approaches, all aimed at finding the right balance of flexibility [9]. L.Yu et al. discusses agent-oriented development in industrial automation and introduces a reference model that integrates agent-orientation through function block technology [10].

Rozo et al. developed a framework that combines learning from demonstration, skills sequencing, and optimization for tasks like e-Bike motor assembly. While emphasizing adaptability and explainability, it requires a significant amount of initial programming and setup [11].

Alternatively, some researchers have been investigating the utilization of offline commissioning methods in their applications to be more flexible and cost effective [7]. Tsarouchi et al. focuses on creating Human-Robot Collaborative (HRC) workspaces that can be adjusted and optimized to meet changing production needs [12].

Recent studies have highlighted the role of Modular Automation Systems (MAS) and Reconfigurable Manufacturing Systems (RMS) in addressing these challenges. The modular design of machines allows for the rapid adaptation of production systems, essential for handling a diverse range of products [13]. The integration of industrial robots into modular designs enhances flexibility and cost-effectiveness [14]. Furthermore, the incorporation of mobile robots into Reconfigurable Production Systems (RPS) is a strategy that can support manufacturing flexibility. Weber et al. conducted research on Mobile Assembly Units (MAUs) as a solution for changeable assembly lines in manufacturing. Their modular concept integrates industrial robots into the assembly process [15].

This paper presents a strategy for enhancing manufacturing flexibility by introducing solutions that integrate into various manufacturing lines. These adaptable solutions are referred to as Automation Packaged Solution (APS). In the upcoming sections the concept of APS will be explained along with two practical applications designed for assembly lines: one for precise screwing and the other for accurately applying product labels. To illustrate the practical impact of these solutions, a case study was conducted at a manufacturing facility in Sweden, demonstrating the integration of two APSs into their assembly line operations.

2. Developing APS

Developing an APS involves establishing a standardized foundation while maintaining the adaptability required for diverse material sizes and specific applications. The essential building hardware of these standard APS packages include industrial robots, vision systems, PLCs (Programmable Logic Controllers), and HMIs (Human-Machine Interfaces). Another aspect of APS development focuses on computer-based simulations, standard programming guidelines, and virtual commissioning. These elements aid in reviewing and optimizing APS designs before actual implementation. The method used to conduct this research is based on experience gathered from implementation of multiple cases on the production line, after which subsequent observations and analyses were performed to assess efficiency of the implemented measures. In this section, the APS components will be explained, and it will be demonstrated how it contributes to the development of the APS.

2.1. Building Blocks of APS

2.1.1. Robot

Robots are the primary components within the APS and the selection of the appropriate robot depends on specific application requirements, including payload capacity and reachability. In cases of frequent human-robot interaction, collaborative robots, often referred to as cobots, are preferred. These robots are designed for safe operation alongside human workers. When applications require greater safety precautions or if collaborative operation is not feasible due to factors like higher velocity needs, industrial robots are used. Additional safety equipment, such as laser scanners, can establish a secure interaction zone for human workers. Alternatively, the entire cell can be fully enclosed to ensure complete isolation from the robot.

In APS development, customizing the size and type of robots to align with specific application demands is essential. This study primarily focuses on robots with smaller working zones, which are well-suited for compact cell configurations. The complete list of factors to consider in the selection process of robots goes beyond payload and reachability. This can be seen in Table 1 .

2.1.2. Vision System

Vision systems are employed for quality control and robot guidance within the APS. These systems use vision algorithms to recognize and adapt to variations in product appearance and positioning. This adaptability allows them to compensate for product differences and assist the robot end effector in achieving precise task execution, even with part tolerances. After task implementation, the vision system conducts quality control to verify correct task execution. If defects are detected, the system can automatically trigger corrective actions, such as task repetition or immediate error notification to the operator. Future APS versions will incorporate AI algorithms to enhance defect detection capabilities. As was the case with the robots, vision systems too encompass several factors that need to be thought about according to the application at hand. This can be seen in Table 2.

Table 1. Key Factors in Robot Selection

Factor	Description
Robot Type	Specify the type of robot (e.g., SCARA, articulated, delta) suitable for the application.
Payload capacity	Determine the robot's capacity to handle different material sizes.
Reach	Define the robot's reach, ensuring it can access all required areas.
End-effector type	Consider the appropriate end-of-arm tooling for the task.
Accuracy and precision	Assess the robot's precision for specific applications.
Speed	Determine the required speed for efficient material handling.
Safety features	Ensure the robot's safety features align with the application.
Integration with vision systems	Plan for integration with vision systems for guidance.

Table 2. Key Factors for Vision System Selection

Factor	Description
Type of Vision System	Choose between 2D and 3D vision systems based on needs.
Resolution	Consider the required level of detail in image processing.
Calibration	Ensure accurate calibration of vision systems for measurements.
Lighting	Determine the appropriate lighting conditions for optimal vision.
Image Processing Algorithms	Select relevant algorithms for classification, object detection, and segmentation.
Real-Time Processing	Plan for real-time image processing if necessary.
Integration with Robots	Ensure seamless integration with the robotic system.

2.1.3. PLC

The APS system integrates a PLC with a safety system for enhanced control and monitoring. The PLC serves as the central control element within the APS, supervising various components such as pre-defined logic, vision systems, sensor data, and communication with the production line. Its role is to coordinate the actions of all APS equipment and gather essential operational data. Furthermore, the APS system can be equipped with remote I/O technology, allowing integration of the PLC into the manufacturing network. This integration enables the manufacturing system to access and exchange data across the network. The PLC factors that need to be taken into account can be seen in Table 3.

Table 3. Key Factors for Selecting the PLC

Factor	Description
PLC Type	Select the appropriate PLC model for control and automation.
Input/Output (I/O) Requirements	Define the number and types of I/O points.
Programming Language	Choose the programming language suitable for the task (e.g., ladder logic, structured text).
Interfacing with Robots and Vision Systems	Plan for communication protocols and interfaces.
Safety Interlocks	Implement safety features using the PLC.
Redundancy	Consider redundancy for critical applications.
Scalability	Ensure the PLC system can scale to accommodate future needs.

2.1.4. HMI

The HMI complements this integration by providing operators with real-time access for monitoring, control, and troubleshooting of the APS, ensuring immediate operator involvement when necessary. The factors pertaining to the HMI selection can be seen in Table 4.

Table 4. Key Factors for Effective HMI Design

Factor	Description
HMI Design	Design an intuitive and user-friendly HMI interface.
Screen Layout	Plan the layout of screens for ease of use.
Control Elements	Choose the appropriate control elements (buttons, sliders, etc.).
Data Visualization	Determine how data from robots and vision systems is presented.
Alerts and Notifications	Include mechanisms for alerts and notifications.
User Training	Consider user training for efficient HMI operation.
Security	Implement security measures to protect the HMI system.
Integration with PLC and Robot Control	Ensure seamless integration with control systems.

2.2. APS Development Process

Making decisions about individual factors in selection of robots, vision systems, line controllers and interfaces between PLC and other components of the system, as well as HMI design considerations need to be assessed in a case by case manner. The shear incompatibility of these factors due to their quantitative and qualitative characteristics alongside their contextual relevance to the project at hand could make it difficult to compare them subjectively. Prioritizing one factor over another should be done according to station's specific requirements and the overall objectives of the project. However, as a general guideline, it can be argued that quantitative factors such as payload capacity, reach, and speed of the robot can help ensure the system meets the technical requirements, while qualitative factors such as safety features, HMI design modules, and integration protocols can help ensure the system is user-friendly, safe, and reliable.

2.2.1. Simulation and Virtual Commissioning

Simulations in APS development provide insights into various aspects, including cycle times, feasibility assessments, layout control, and the optimization of robot paths. These simulations also play a key role in virtual commissioning, helping prepare the programming and communication architecture of the cell before physical implementation. APS development prioritizes programming standards to ensure consistency and clarity in the coding and control logic of APS systems.

2.2.2. Quality Control and Data Analysis

APSs are equipped with inspection, defect, and error detection capabilities, which enhance quality control by identifying anomalies during the process. Additionally, a data analysis system processes data generated during the automation process. Various data analysis techniques, including statistical analysis and data visualization, are employed to extract insights from the data generated by APS operations.

Having established the building blocks of the APS, an iterative process starts to optimize all the components and then evaluate performance of the overall system. The process will continue until either a convergence condition is met, or the system's performance reaches the minimum satisfactory level. This optimization can be done over the entire system to optimize the selection of industrial robots, vision systems, PLCs, and HMIs for a standardized robotic-based automation system, or it can be repurposed to optimize only a selected number of components within the system. A high-level pseudocode for this optimization problem can be seen in Algorithm 1.

3. Test Cases

In this section, two APS test cases will be explained, both of which have been designed and integrated into the production line of a Swedish manufacturing company. Depending on the specific task, supplementary tools and equipment are introduced into the automation solution. This production line is responsible for manufacturing four different product models, each varying in size and color. Both cases are related to the same line where a sequence of operations are followed to assemble the final product.

3.1. Screwdriver- APS

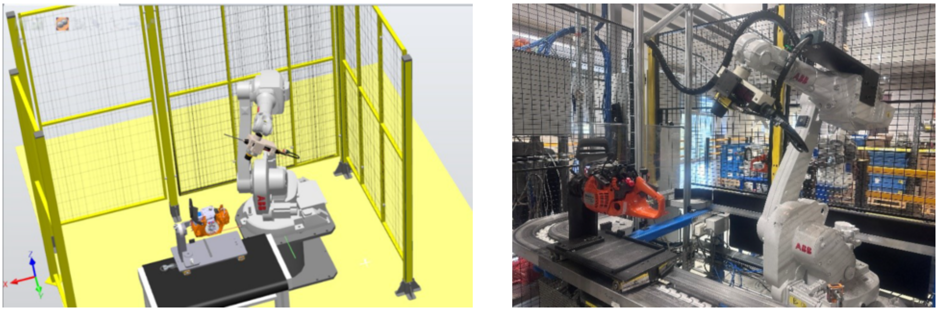
In several studies, it has been demonstrated that approximately 27% of assembly tasks and 37.9% of mechanical assembly operations involve fastening procedures ([16], [17]). This emphasizes the importance of designing a Screwdriver-APS to automate component screwing within the assembly process, as exemplified in the current study with the screwing of the filter holder. The development of the Screwdriver-APS involves the use of a six-axis industrial robot, along with the integration of additional components such as an electric transducerized screwdriver and a corresponding screw-feeder system into the basic APS framework (Figure 1).

The Screwdriver is capable to provide precise torque control and enables the collection of torque-related data for each product in the manufacturing SCADA system. It is equipped with real-time feedback to the control system, indicating whether the screw has been tightened to the specified torque level. The torque level can be adjusted for specific

Algorithm 1 High-Level Optimization Pseudocode for APS

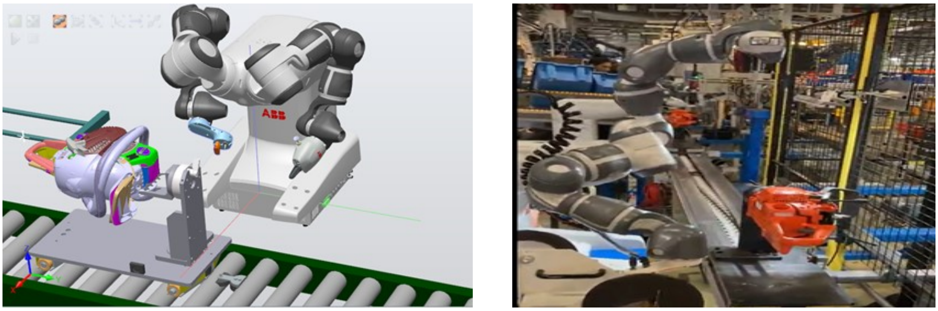
```
best_configuration = {}                                   ▷ A dictionary to store the best configuration
best_performance = 0
                                                          ▷ Define a function to optimize a component
function OptimizeComponent(component_type, parameters)
    best_component_config ← None
    best_component_performance = 0
                                     ▷ Evaluate performance based on parameters and historical data
    for configuration in available_configurations[component_type] do
        component_performance = evaluate_performance(config, parameters)
                                                ▷ Check if this configuration improves performance
        if component_performance > best_component_performance then
            best_component_config = configuration
            best_component_performance = component_performance
        end if
    end for
                                                ▷ Update the best configuration for this component
    best_configuration[component_type] = best_component_config
end function
                                                                      ▷ Main optimization loop
while not convergence_condition do                                 ▷ Define the convergence criteria
                                                                      ▷ Optimize each component
    OptimizeComponent('IndustrialRobots', best_configuration)
    OptimizeComponent('VisionSystems', best_configuration)
    OptimizeComponent('PLCs', best_configuration)
    OptimizeComponent('HMIs', best_configuration)
                                                  ▷ Update the system with the best configuration
    update_system(best_configuration)
                                                              ▷ Measure the system's performance
    system_performance = evaluate_system_performance(best_configuration)
                                                     ▷ Check if the system's performance is better
    if system_performance > best_performance then
        best_performance = system_performance
                                      ▷ If performance didn't improve, adjust parameters or algorithms
    else
        adjust_parameters()
    end if
end while
                                          ▷ Configure the system with the best overall configuration
configure_system(best_configuration)
```

screw fastening tasks based on the model in the control system, offering flexibility in the assembly process. Additionally, a customized 3D printed end effector is designed to hold the screwdriver, along with the 2D vision system programmed to locate the correct hole positions based on each production model on the production line (Figure 3).



(a) (b)

Figure 1. a: Screwdriver-APS Simulation, b: Installed Application



(a) (b)

Figure 2. a: Labeling-APS Simulation, b: Installed Application

(a) (b)

Figure 3. 3D-Printed Robot End-Effectors for APS Applications - a: Labeling-APS, b: Screwdriver-APS

3.2. Labeling-APS

Labeling-APS is designed to automate label application on products within the assembly line (Figure 2). Its development involves utilizing a dual arm cobot and the integration of a label dispensing mechanism for supplying labels to the cell. The vision system in this APS identifies label positions on the dispenser and instructs the robot on where to place them.

Each robot arm is equipped with an end effector. One end effector holds and applies labels using a 3D-printed suction cup holder, while the other is equipped with the 2D vision system which also verifies the quality of the label application (Figure 3).

4. Results

The implementation of APS brings about positive changes across various aspects of the manufacturing and assembly processes.

4.1. Labor Optimization

One outcome of APS implementation has been the reduction in labor requirements. Prior to APS integration, the assembly line was reliant on 13 operators. However, with the adoption of these automation solutions, the workforce requirement decreased to 12 operators. This transition signifies a 7.7% reduction in labor, marking an early accomplishment in optimizing workforce utilization.

4.2. Enhanced Overall Equipment Efficiency (OEE)

The APS solutions have impacted the OEE of the assembly line. Detailed assessments have shown approximately 10% increase in OEE, primarily attributed to the automation of critical tasks, such as precise screwing and accurate label placement. In the most recent evaluations, both the Labeling-APS and the Screwing-APS have achieved OEE ratings exceeding 95%. This demonstrates improvements in operational efficiency, resulting from reduced downtime, heightened production rates, and enhanced quality control.

4.3. Reduction in Screw and Label Waste

The implementation of APS has significantly reduced screw and label waste originating from incorrect installations. The error detection and quality control systems integrated into the Labeling-APS ensure the accurate and precise application of labels, eliminating issues like wrinkles or misalignment. This, in turn, leads to a substantial reduction in waste and material costs. The minimized waste not only translates into cost savings but also aligns with a more sustainable and eco-friendly approach to manufacturing.

4.4. Rebalancing for Reduced Cycle Time

APS's adaptability swiftly optimizes the assembly line when the need for reduced cycle times arises. It enables rapid adjustments and reconfigurations, leading to a reduction in production cycle time. This flexibility maintains manufacturing agility, ensuring adaptability to evolving demands. By implementing the APS that was developed for the abovementioned cases, a 6 second reduction in the cycle time was achieved. A remarkable aspect of this improvement was attributed to the overall handling of this change which was mainly to due the ease of working with APS implementation on the production line.

4.5. Ease of Relocation and Integration

One of the advantages of APS is the simplicity of relocating these automation solutions to different sections of the production line. This is a direct result of the standardized programming and virtual commissioning utilized during APS development. When the situation demanded the relocation of APS to address new production requirements, the transition was easy to integrate and time-efficient (Figure 4). The result is that these solutions can be easily integrated into different parts of the production line with minimal disruption, enhancing the overall adaptability and productivity of the manufacturing process.

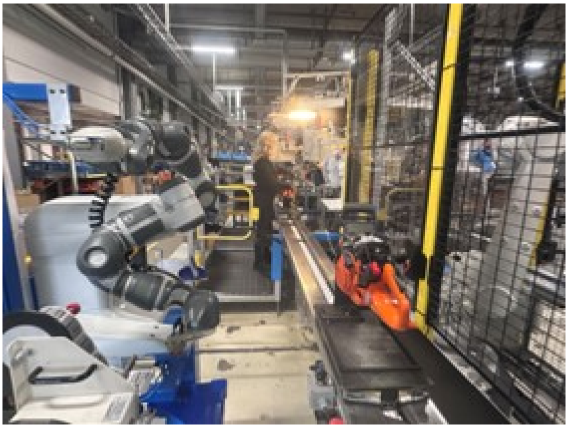


Figure 4. Relocated Labeling-APS with Side Label Placement Adaptation

4.6. Rapid Integration of New Product Models

In addition to relocation and rebalancing, APS's standardized programming and virtual commissioning play a crucial role in facilitating the integration of new product models into the assembly line all achieved without the need for extensive reengineering and reprogramming. The ability to add new products with minimal lead time emphasizes the efficiency and necessity of APS solutions.

5. Discussion

For providing an automation solutions, it's essential to make a smart choice that aligns with the specific needs of the operations, promising efficiency, scalability, and reliability. This discussion aims to compare APS with two alternative approaches: MAU and MAS. Both have been explored as an option to enable changeable assembly lines, offering advantages in terms of flexibility. However, they also come with complexities and involving multiple customized components and connections, demanding careful design and ongoing maintenance.

However, APS offer simplicity and ease of integration which provides easier maintenance and ensuring that the operations run smoothly. Compared to MAUs and MAS described in the literature, APS offer advantages in terms of simplicity and speed of deployment. They are designed for rapid implementation, significantly reducing downtime. In addition, APS focus on scalability and adaptability with cost-efficiency and minimizing initial investment and ongoing operational expenses. They can be easily expanded by adding more stations or robotic units as needed. MAUs and MAS, while flexible, can entail higher costs and scalability limitations, especially when reconfigurations are frequent due to complex reconfiguration processes.

APS also come equipped with a built-in quality check system, adding another layer of efficiency and ensuring the production of high-quality outputs. Furthermore, as technology evolves, APS are well-positioned to integrate AI-based systems in the future. This additional feature enhances their appeal, making them even more robust and future-proof.

6. Conclusion

The concept of APS provides a flexible approach to automation. APSs are designed to automate specific tasks, and their key advantage is the capacity to adjust to new products without requiring extensive reengineering or reprogramming. These solutions rely on computer simulations and offline commissioning to streamline the integration of robotics and vision technologies. Case studies have demonstrated the practical impact of APS in enhancing manufacturing flexibility and efficiency. The flexibility of APS design allows for quick adjustments to meet specific operational needs.

Moreover, the adoption of 3D printing technology in constructing robot end effectors reduces costs and enhances adaptability in the manufacturing process. Advanced simulations are employed to adjust robot paths and configurations swiftly, ensuring minimal disruptions and maximum adaptability in response to changing manufacturing needs.

The integration of vision systems in APS enhances adaptability by recognizing product variations. Moreover, vision systems play a pivotal role in quality control and robot guidance. A standardized foundation in APS packages ensures compatibility with diverse material sizes and specific applications and its data analysis capability contributes to process optimization, predictive maintenance, and continuous improvement of system performance. These strategies offer cost-effective solutions for the dynamic industrial landscape, emphasizing the importance of efficiency.

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