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RESEARCH ARTICLE

Development of a Novel Methodology to Retrofit Legacy Systems in the Context of Industry 4.0

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ABSTRACT This research aims to develop a comprehensive methodology for retrofitting legacy industrial automation systems, encompassing hardware and software updates, testing, and validations, to ensure that the system aligns with current and future needs. The proposed methodology not only addresses technical aspects but also considers the integration of emerging technologies such as the Internet of Things (IoT), cyber-physical systems, cloud computing, and digital twins. The main goal of the retrofitting process is to enhance the efficiency, integration, security, and interoperability of the legacy system, enabling it to remain competitive in the long term. Legacy systems may require retrofitting for various reasons, including incompatibility with new devices or technologies, inability to meet the current needs of the manufacturing process, vulnerability to security threats, or noncompliance with current industry standards and regulations. Through the proposed methodology, step-by-step guidance will be provided, enabling organizations to successfully update their legacy systems using retrofitting techniques and capitalize on the advantages offered by Industry 4.0.

INDEX TERMS Methodology, retrofitting, legacy system, virtual model, architecture.

I. INTRODUCTION

Industry 4.0 (I4.0) refers to an approach that aims to enhance industrial processes' efficiency and flexibility by boosting various technologies. According to [1] and [2], I4.0 defines the key technologies, characteristics, and applications, with the primary goal of connecting all aspects of the production process and creating an integrated, adaptable, and autonomous system.

I4.0 includes a range of key technologies, such as the Internet of Things (IoT), cloud computing (CC), cyber-physical systems (CPS), and big data (BD). These technological advancements facilitate the real-time monitoring and control of the production process, leading to improved performance optimization, cost reduction, and enhanced product quality.

Among these technologies, there is the digital twin (DT) [3], which is a virtual representation of a physical object or process that allows simulation and analysis of the behavior of the real system. It is built from data collected from the real world and can be used for the development of simulations, predictions, optimizations, and monitoring.

Several applications of digital technology provide an optimistic outlook for investigating DT architecture that emphasizes I4.0 applications and concepts, as well as intelligent

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systems [4] and updates to legacy systems [5], among others [6], [7]. A focus on legacy systems, which refer to systems designed and implemented using outdated technologies and architectures, is particularly interesting because the utilization and upgrade of these systems provide cost reduction, increased lifetime, and improved processes.

In [8], the concept of retrofitting a legacy system can be defined as the process of updating or modernizing a legacy system, usually with the purpose of improving its performance, security, or functionality. Therefore, there are several reasons to carry out the retrofitting of a legacy system. For example, it may be that the legacy system is not compatible with new devices or technologies or that it no longer meets the current needs of the process. In addition, the legacy system may be vulnerable to security threats or may not comply with current standards or regulations.

The proposal of retrofitting is an approach to update legacy manufacturing systems, aiming to meet the requirements that represent the concept of Industry 4.0. Thus, this work proposes a step-by-step methodology that enables the updating of a legacy system using retrofitting techniques.

A. MOTIVATION AND CONTRIBUTION

It is worth noting that retrofitting a legacy system can be a complex and expensive process, as it may require updating the software and involving many stages of testing and validation to ensure that the updated application meets the current and future requirements of a process.

The main goal of this work is to develop a methodology for updating legacy systems using retrofitting techniques. The process starts with an assessment of the legacy system's requirements, as well as an evaluation of its features and limitations. Consequently, the goals and prerequisites for implementing the retrofitting process will be established.

In the retrofitting process, key technologies of I4.0 will be updated in the legacy system, allowing data from the physical system to be collected and processed to feed the virtual model. The information from the physical system and the virtual model are integrated, allowing for continuous monitoring and evaluation of the performance of the system being updated and the results obtained concerning the established goals.

The main contribution is the retrofit methodology with the step-by-step implementation guide. The retrofit involves updating old and obsolete devices to newer devices that are more advanced and includes new technologies related to I4.0 to improve efficiency, integrate and streamline the process, improve performance, safety, and system interoperability, providing an economical solution by allowing the use of existing facility devices and reducing investment costs.

The proposed methodology will integrate technologies, making the legacy system technologically advanced enough to interact and integrate with current systems. The intent is to provide a structured and systematic method to update legacy systems by identifying the requirements and defining the goals and assumptions needed for retrofit implementation. Thus, the step-by-step guide outlines a clear and concise process for retrofitting. By following the steps provided, it is possible to systematically update the legacy systems and ensure that they meet the requirements of I4.0.

II. RELATED WORKS

Retrofitting is an increasingly common practice in the industry, as it allows for the updating of systems and equipment to take advantage of newer technologies and increase the efficiency and competitiveness of the process.

Industry 4.0 is changing the way retrofitting is applied [9], with the increasing use of additive manufacturing technologies and digital simulation to design and test new retrofit solutions. Currently, there are several approaches and technologies available for implementing retrofit techniques, such as programmable controllers, industrial communication networks, automation systems, and Internet of Things (IoT) technologies.

The goal of this section is to review and analyze the literature on base retrofitting. The purpose is to gain an understanding of the current state of this topic and its developmental trends. By examining prior research on this subject, this study aims to identify any gaps or areas of interest and ultimately position its new contribution.

The section intends to provide an overview of the research already conducted in the field of base retrofitting. This includes analyzing previous works related to the topic to gain insight into the existing knowledge, concepts, and methods used in this field.

A. SYSTEMATIC REVIEW

In [10], a systematic literature review is proposed to analyze the scientific literature on the application of smart technologies in modernizing and updating existing factories and manufacturing systems (through retrofitting).

The review provides an overview of the main types of technologies employed, as well as the challenges and opportunities encountered by companies in implementing these technologies. In addition, a discussion on the potential benefits that can be obtained was presented, such as improved operational efficiency, cost reduction, and increased quality.

In [11], a study on the modernization and updating of existing manufacturing systems, known as legacy systems, to meet some of the requirements of I4.0 was proposed. Industry 4.0 is characterized by connected, automated, and intelligent systems, and the goal is to show how these characteristics can be added and integrated into older systems through retrofitting.

The author presents the main trends and challenges in [11] the implementation of retrofitting for legacy systems, including the need to address the lack of compatibility between old and new technologies, the lack of resources for implementation, and the complexity of the implementation. The importance of collaboration among companies, suppliers, and customers to maximize the benefits of I4.0 is also highlighted.

In [12], a review of the challenges and applications of real-time digital models of physical systems, also known as "digital twins", was presented. The challenges related to the use of digital twins, such as modeling and simulation, integration with physical systems, data management, and security, are discussed in detail.

The author emphasizes the potential of artificial intelligence and advanced data analytics in [12], creating more sophisticated and effective digital twins. By using data analysis, the accuracy of the models can be improved, and artificial intelligence can be employed to optimize the physical system's performance.

The objective of the study is to provide an overview of the current state of knowledge about digital twins and identify the primary trends and challenges of the implementation of technology. The possibility of updating legacy systems through retrofitting techniques and methodologies is also discussed.

B. LEGACY SYSTEM

In [13], an approach is presented for achieving interoperability in industrial cyber-physical systems, particularly in legacy systems that were often not designed to possess this feature. Interoperability is the ability of different systems, devices, or components to work together in a compatible manner.

The author lists the main challenges in implementing cyber-physical systems, including the diversity of devices and protocols, the lack of standardization, and the need for integration with legacy systems [13]. The approach presents a reference architecture based on web services and the implementation of middleware to ensure communication between the systems.

The proposed approach also employs gateways, which facilitate communication between existing systems, enabling data collected by older systems to be shared and accessed by modern systems. In addition, older systems can take advantage of the capabilities of modern systems by using gateways to connect them.

In [14], the application of WebAssembly (Wasm) technology for modernizing and updating legacy industrial production systems is discussed, making them more efficient and safer. The idea is to use WebAssembly technology to execute code on edge devices, which reduces latency and increases processing speed and connects these devices to old machines. This would allow data collected by old machines to be processed and transmitted in real time, enabling monitoring and control of industrial operations.

Examples of using WebAssembly technology for retrofitting old industrial machines are detailed, and the advantages of using this approach are discussed, such as the ability to process large volumes of data and the possibility of developing predictive maintenance applications and security solutions.

A case study is presented in Wasm technology, which was used to improve the efficiency of an automobile production system. The case study shows how Wasm was used to run data processing directly on the machine without the need for additional cloud computing resources.

The paper [15] focuses on the topic of servitization in the context of Industry 4.0 and proposes how companies can adapt their existing manufacturing systems to provide value-added services. Servitization is the process of providing not only products but also related services such as maintenance, monitoring, and support.

Specifically, the paper explores how legacy manufacturing systems can be updated to offer innovative services in addition to their core products. This approach helps companies stay competitive in the ever-evolving Industry 4.0 landscape. The work presents a case study of a company that successfully implemented servitization in its legacy manufacturing system, as well as a checklist for companies wishing to adopt servitization.

The Industrial Internet of Things (IIoT) and retrofitting of legacy machines are examined in [16], providing a comprehensive overview of their benefits, obstacles, and potential impact on the operational efficiency of companies.

According to [16], IIoT involves connecting devices and machines to gather and exchange data in real time, resulting in improved monitoring and control of industrial operations. The retrofitting of legacy machines, which involves updating outdated equipment to ensure compatibility with modern technologies, is also discussed. This study emphasizes the significance of retrofitting in achieving successful IIoT implementation, given that many companies still utilize old and often outdated equipment that needs to be updated to reap the benefits of IIoT.

In [17], the upgrading of traditional production systems to cyber-physical production systems (CPS) in I4.0 is discussed. The concept of I4.0 and its relationship with the digitization and automation of industrial production, focusing on the integration of information and communication technologies with production systems to improve efficiency and process quality, was presented.

Additionally, details about how CPS combines digital and physical technologies to create flexible and intelligent systems that can quickly adapt to customer needs were presented. The challenges faced in retrofitting traditional systems to CPS are discussed, mainly related to the lack of compatibility between technologies and the need to change internal company structures.

A case study is presented to illustrate the application of retrofitting in a cyber-physical production system. The author highlights the advantages of retrofitting, including improved efficiency and process quality, while also noting the challenges faced by the company during the process.

In [18], the application of machine learning techniques to analyze machine vibrations and identify possible maintenance problems was proposed. The goal is to use this solution in old machines that do not have precise parameters available. The proposal allows maintenance engineers to make more accurate decisions, thus improving process performance. The solution can detect anomalies in the machine, and vibration analysis can be used to monitor machine performance over time.

C. BROWNFIELD

In industry, when referring to a product, the term "Brownfield" is used for the process of updating legacy systems. According to [19], the term is applied when the project's product is designed to complement something that already exists in situations where there are already facilities and installations into which the project's product will be incorporated.

The term "Brownfield" specifically applies to the updating of systems or production processes that are already in operation, while the term "Greenfield" applies to the construction of a new system or production process.

In [8], a retrofit-based approach is presented for developing Industry 4.0 solutions in existing processes, referred to in the text as Brownfield. This term refers to an existing production facility that needs to be adapted to new technologies. The paper then presents a methodology for retrofitting equipment to make them capable of communicating with other equipment and systems within the company to impotency and reduce costs.

The proposed methodology shown in [8] includes an analysis of technical and financial feasibility, the definition of requirements for integrating legacy equipment with Industry 4.0 technologies, and the selection of the most suitable hardware and software solutions for retrofitting. Some examples of how this approach has been applied are presented, and the challenges and benefits of using the methodology are discussed.

The proposal presented in [8] comprises six fundamental stages: 1) current situation assessment, 2) goal and objective definition, 3) technology selection and integration, 4) system design, 5) implementation, and 6) operation and maintenance. The paper provides details about Brownfield factory retrofitting, encompassing cybersecurity and scalability aspects. These stages can be employed as a retrofitting strategy.

In [19], the challenge of implementing intelligent manufacturing technologies (smart manufacturing) in Brownfield systems was addressed. It offers a methodology for updating old systems and making them intelligent, facilitating the transformation of the legacy system to the Industry 4.0 concept.

The author presents a retrofit approach based on three stages: (1) identification of retrofit requirements, (2) selection of appropriate technologies, and (3) implementation of selected technologies. A case study of an aircraft parts manufacturing company was discussed that modernized its legacy systems through the implementation of smart manufacturing technologies. The case study illustrates how modernizing legacy systems can significantly improve production efficiency and reduce cost.

D. RETROFIT

Retrofit is the process of adding new technologies or improvements to an existing system or equipment. This can be done to increase efficiency, add new functionalities, or update the system to meet new regulations or standards.

To carry out retrofitting or Brownfield, some specific prerequisites are necessary. First, identify the goals of the update to define the appropriate strategy and action plan. Then, the current system or process is analyzed to identify the problems and strengths, as well as the requirements and constraints of the update. Finally, the components and technologies to be updated are selected in a way that is adherent to the objectives and goals of the update and that follows the requirements and constraints of the current system or process.

According to [20], retrofitting can be performed on a wide range of systems and equipment, including buildings, vehicles, industrial machines, and information systems. Some of the common reasons for retrofitting include the need to update obsolete technologies, reduce operating costs, improve safety or energy efficiency, and comply with new regulations or performance standards.

III. PROPOSED METHODOLOGY

The retrofit methodology can be used to update and improve the performance of legacy systems without the need to build a new system. The digital twin architecture allows for the creation of a real-time digital model of a physical system. This allows control engineers to simulate the behavior of the system under different conditions, which can help optimize performance and reduce costs.

The retrofit methodology and digital twin architecture can be used to significantly improve the performance of existing systems and make them more efficient and safer. The methodology can be used to update specific components or subsystems, while the architecture can be used to simulate and monitor the entire system in real time.

A. REQUIREMENTS TO APPLY RETROFIT

Some general requirements for performing a retrofit are presented by [21], shown in an adapted form in Fig. 1, and summarized as follows:

- Identify the system or equipment that needs retrofitting and define the retrofitting goals, such as increasing efficiency, adding new functionalities, or updating the system to comply with new regulations or standards.
- Perform a detailed assessment of the current system or equipment to identify which components need to be upgraded or replaced.
- Design improvements or updates that will be made, including the selection of new technologies or components.
- Obtain all necessary approvals or licenses to perform the retrofitting.

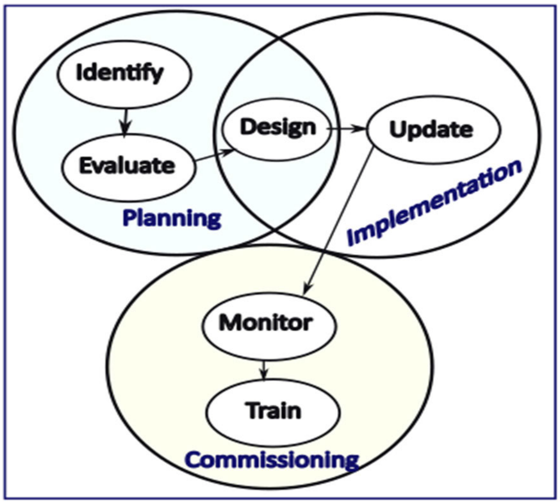


FIGURE 1. Requirements to apply retrofitting. Adapted from [21].

- Shutdown the system or equipment and remove all old or obsolete components from the system.
- Install the new technologies or components and test the system or equipment to ensure it is working properly.
- Monitor the performance of the system or equipment after retrofitting to ensure that it is achieving the established goals.
- Train the personnel responsible for the system or equipment on how to use and maintain the new technologies or components.

B. DIFFICULTIES IN APPLYING RETROFIT

To achieve the technologies used in the concept of Industry 4.0, using methodology and architecture, it is important to consider which methods and techniques can be applied and which technologies are of interest for the application, which comes through the gathering of system requirements.

This includes outlining a strategy to achieve the established goals and then establishing steps from problem definition and characterization, data collection, data analysis, and interpretation of results.

Thus, some difficulties in the application of retrofitting can be identified, which are summarized below:

- Compatibility of technologies: older technologies may not be compatible with the new technologies used for retrofitting, which can make the implementation of the methodology difficult.
- Lack of resources: Implementing retrofitting can be costly and may require additional resources, such as time, specialized labor, and advanced technologies. Such resources may be difficult to obtain.
- Changes in processes: Retrofitting may require changes in existing processes, which can be difficult to implement and may cause interruptions in the production process.
- Difficulty in monitoring: It may be difficult to monitor and manage the machines and equipment to which retrofitting methodologies have been applied, especially if they are distant or if there are connectivity problems.
- Lack of training: It may be difficult to ensure that system users are trained and capable of operating and maintaining updated equipment.

To achieve a successful retrofit, it is crucial to recognize that technological and retrofit implementation limitations may occur, particularly when systems are too old to be updated. Therefore, it is essential to perform a reliable evaluation and gather all requirements of the legacy system to ensure the retrofit's success.

C. STEP BY-STEP TO APPLY RETROFIT

To update a legacy system using retrofit techniques, it is necessary to initially identify and define the goals of the update and the process to increase efficiency and reduce costs, such as improving quality and increasing security, among other desirable objectives.

Then, perform a detailed analysis of the legacy system, identifying its components, dependencies, interactions, problems, and limitations to select the technologies that will be used to update the system, considering the update goals and the characteristics of the legacy system.

In the retrofit process, it is necessary to define the components, procedures, and processes that will be modified or added to later perform necessary tests, adjustments, and user training. Thus, according to [22], retrofit application in legacy systems is a modernization or update process of existing systems or production processes to make them more efficient, flexible, secure, and adaptable to new needs and technologies. This procedure may include adding or replacing components or technologies, as well as integrating information or management systems.

This update is a necessity for companies that want to maintain competitiveness and take advantage of opportunities offered by Industry 4.0 technologies. Among the several benefits are increased efficiency, cost reduction, increased flexibility, improved quality, and agility.

According to [23], to update legacy systems, it is necessary to follow some steps, as presented below:

1) STEP 1 – IDENTIFICATION OF THE GOALS

To define the appropriate strategy and action plans for the update, it is important to identify the goals and objectives, which may include increasing efficiency, reducing costs, and increasing flexibility, among others.

In addition to identifying the goals, it is important to consider all the needs and expectations of the users, as well as the characteristics and particularly of the legacy system. It is also important to assess the expected benefits, risks, and impacts, among other aspects.

2) STEP 2 – ANALYSIS OF THE CURRENT SYSTEM

To ensure a successful retrofit, it is crucial to conduct a thorough analysis of the existing legacy system. This involves identifying its strengths and weaknesses, as well as its requirements and constraints.

During the analysis, it is important to evaluate the individual components and technologies that need to be updated or replaced. This includes determining the expected benefits of the retrofit, assessing any associated risks and impacts, estimating costs, and setting implementation deadlines, among other factors. By taking all these aspects into consideration, a well-informed decision can be made about which components to update and how to proceed with the retrofit.

3) STEP 3 – SELECTION OF COMPONENTS AND TECHNOLOGIES TO BE UPDATED

To ensure successful retrofitting, it is crucial to select the appropriate components and technologies based on the system's requirements and constraints, as well as the defined goals. The following steps should be taken to select the components and technologies:

- Analyze the characteristics and peculiarities of the legacy system to understand the components and technologies that need to be updated or replaced.
- Consider the goals and objectives of the retrofit, including increasing efficiency, reducing costs, and increasing flexibility.
- Assess the risks and impacts of replacing or updating components and technologies, as well as the associated costs and implementation deadlines.
- Carefully select the components and technologies that align with the system's requirements and constraints, as well as the retrofit goals.

By following these steps, it is possible to guarantee that the components and technologies chosen for the retrofit are suitable for the system's needs and will effectively contribute to accomplishing the defined goals.

4) STEP 4 – INTEGRATION OF NEW COMPONENTS AND TECHNOLOGIES

To ensure the integrity and functionality of the system, it is crucial to integrate the new components and technologies in a compatible and coherent manner with the current system or process. The following steps should be considered:

- Evaluate the compatibility of the new components and technologies with the legacy system, considering any potential conflicts or issues that may arise.
- Develop a plan for integrating the new components and technologies into the existing system, considering the specific requirements and constraints of the system.
- Test the integration thoroughly to ensure that the new components and technologies are working correctly and as intended; monitor the system after integration to detect and resolve any issues or conflicts that may arise.

The next step will help to ensure that the integration is successful and that the system functions properly after the retrofit.

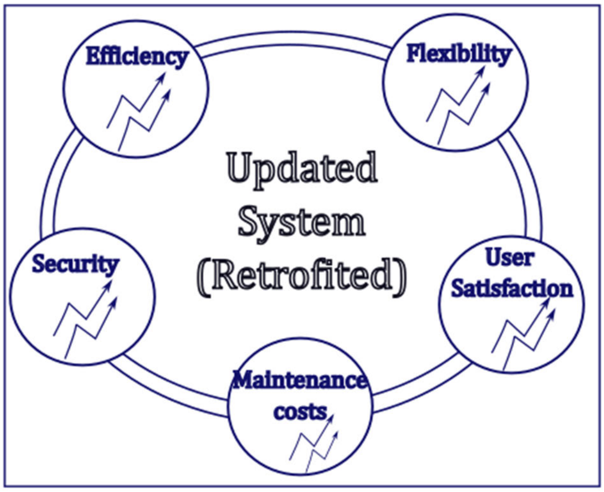


FIGURE 2. Expected results of retrofit. Adapted from [21].

5) STEP 5 – TESTING AND VALIDATION OF NEW COMPONENTS AND TECHNOLOGIES

Thorough testing and validation are essential to ensure proper functionality of new components and technologies, as well as to assess potential risks and impacts, in line with retrofit objectives.

The digital transformation of legacy systems requires the testing and validation of new components and technologies to ensure that the update meets its goals. Organizations may use various testing and validation methods, including manual tests, automated testing, and simulations, as well as different types of tests, such as performance testing, reliability tests, and security tests.

By performing testing and validation, organizations can guarantee that their systems are updated and optimized for their intended purposes. This step-by-step process helps to ensure that the new components and technologies function as expected and that the retrofit objectives are met.

D. EXPECTED RESULTS AFTER THE RETROFIT APPLICATION

As the updating process is ongoing and the systems are technologically outdated (out-of-date), it is necessary to perform monitoring and maintenance of the legacy system update, monitor its functioning, carry out preventive and corrective maintenance, and update components as necessary. Then, after the update implementation, the following expected results can be achieved, as shown in Fig. 2:

- Increased efficiency: It is expected to become more efficient, as new technologies and components can increase processing speed and decrease downtime.
- Increased security is expected to become more secure, as new technologies can include more advanced security measures, such as two-factor authentication and data encryption.

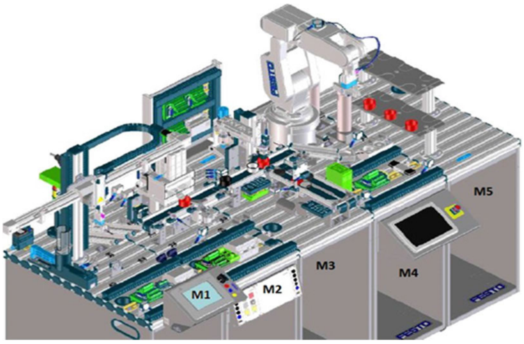


FIGURE 3. **MPS - didactic platform.**

- Increased flexibility: It is expected to become more flexible, as new technologies can allow the system to easily adapt to changes in the company or organization's needs.
- Decreased maintenance costs: It is expected that maintenance costs will decrease, as new technologies can be easier to maintain and update.
- Increased user satisfaction: User satisfaction is expected to increase as the system becomes more intuitive and easier to use.

Establishing acceptance criteria for testing and validation is an important aspect of introducing new components and technologies. These criteria define what is considered acceptable or unacceptable and can vary depending on the objectives, goals, and requirements of the system or process being transformed.

Once the criteria are established, testing and validation can be conducted to ensure that the new components and technologies are ready for implementation. The results of these tests can be used to adjust or correct any problems found as well as to ensure that the system is not interrupted or damaged during the process.

It is crucial to conduct testing and validation in a safe and controlled manner to prevent any issues or disruptions. By implementing these steps, businesses can successfully introduce new technologies and components to improve their processes and achieve digital transformation.

IV. CASE OF STUDY

A. LEGACY SYSTEM DESCRIPTION

The modular producing system (MPS) is a flexible and modular production system manufactured by FESTO [24]. The MPS, shown in Fig. 3, is a didactic platform that allows customization and adaptation of equipment and production processes, considering the specific needs of the project. The platform's main purpose is to provide a teaching tool for practical education in automation.

The focus of the MPS platform is to help teachers and students understand the fundamental concepts of automation and provide practical experience in programming automation systems. As a result, it has been designed to represent a system of production that is flexible and modular. This allows for easy customization and adaptation of equipment and processes to meet the specific needs of a project.

Legacy systems often require updates to keep up with modern technologies and changing needs. Retrofitting a legacy system can involve updating the software, hardware, or both. This process may also involve adding new devices, such as sensors, IoT devices, and artificial intelligence systems, to enhance the system's functionality. Moreover, older devices may need to be replaced with newer devices to improve the system's performance and safety.

1) HARDWARE OF THE HANDLING MODULE

MPS is composed of modules that can be combined and/or rearranged according to the application's needs. The available modules, in this case, are the handling module, the press module, the pick and place module, and the robot module. This study is focused on a handling module such as the case study.

The handling module (M1) is a production automation solution that aims to simplify and optimize the transportation and handling of parts and products on production and assembly lines. It consists of various components, such as robots, transport systems, gripping devices, and measuring devices, that are integrated and centrally controlled to manage the workflow. The handling module can be programmed to perform specific tasks such as picking up, transporting, rotating, and positioning parts according to production needs.

2) SOFTWARE

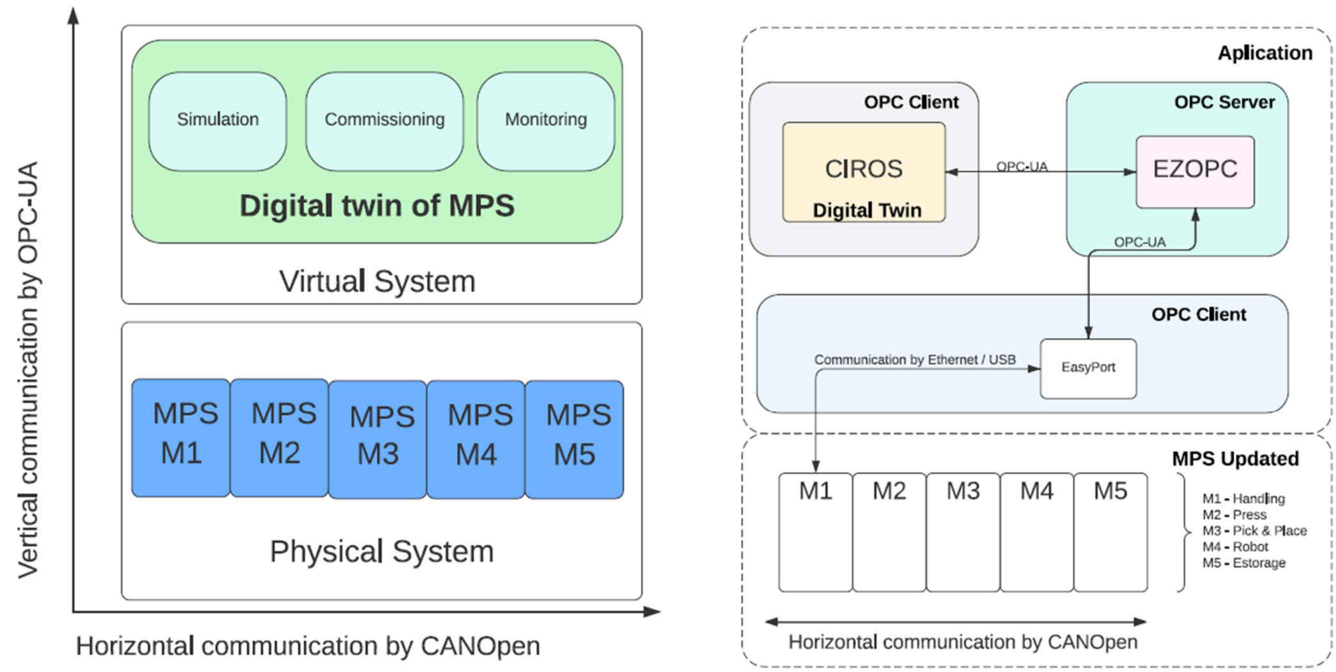
CODESYS is an automation programming software used in the MPS platform [25]. It is used for programming the system controllers and configuring communication interfaces. It allows the user to create, test, and implement control programs for MPS modules such as handling, press, and pick and place.

CIROS is another software used in the system; it is a robotics simulation tool developed by KUKA, a German industrial robotics company [26]. The software allows users to design, program, and simulate industrial robot systems in a virtual environment before implementing them in real life. It also allows users to test different scenarios and configurations to optimize the performance and efficiency of the robot system.

B. METHODOLOGY APPLIED ON THE MPS HANDLING MODULE

The MPS handling module is an example of a legacy system that could benefit from a retrofit. This section will present a methodology for retrofitting this module. The methodology follows the guidelines and steps previously mentioned, detailing the implementation of each stage clearly and concisely. The methodology includes the necessary activities for the development and application of the retrofit solution.

Digital twin technology can be applied to legacy systems as a methodology for retrofitting. By creating a digital twin



(a) Horizontal and vertical communication

(b) EasyPort communication

FIGURE 4. Additional updates.

of a legacy system, engineers can simulate and test different retrofit options, allowing them to optimize the retrofitting process and ensure that the new technology will work seamlessly with the existing system.

By using sensors and other monitoring devices to gather data on the physical system, users can detect potential issues early on and make proactive repairs, reducing downtime and extending the lifespan of the system.

In addition, retrofitting a legacy system is an effective solution for updating and modernizing older systems. The methodology presented in this section can be used to retrofit the MPS handling module, and in the future, other legacy systems in need of updating.

After performing the testing and validation, the updated system should be implemented and put into operation, considering the characteristics and particularities of the system, the objectives of the retrofit, risks, and impacts, among other aspects. Adequate maintenance and support of the updated system ensures its proper functioning and availability.

C. FOLLOWING STEPS AND EXPECTATIONS AFTER THE UPGRADE

Defining the retrofit goals is an important step because it helps to guide the rest of the retrofitting process. By having a clear understanding of what you want to achieve, you can focus on finding the best retrofit options and evaluating their impact on the system.

Creating a digital twin typically involves three steps: data collection, data processing, and model creation. During the data collection phase, sensors and other monitoring devices are used to gather data about the system's behavior and performance. These data are then processed and organized to create a dataset that can be used to create a model of the system.

Simulating retrofit options involves using the digital twin to create virtual models of the retrofit options and testing them in a simulated environment. This allows you to evaluate the impact of each option on the system's performance, efficiency, and other key factors.

Simulating different options also allows you to identify any potential issues or problems before implementing the retrofit in the physical system.

Assessment of the results typically involves using data analytics tools and software to evaluate the data gathered from the digital twin. These data can be used to identify trends, patterns, and other key factors that influence the system's performance. Based on this analysis, you can identify the retrofit option that best meets the retrofit goals.

After the retrofit has been implemented, the digital twin can be used to monitor the performance of the system and ensure that the retrofit is working as intended. Any issues or problems can be identified early on and addressed before they become more serious. Monitoring the system also allows you to gather additional data and refine the retrofit.

D. ADDITIONAL UPDATES PROPOSED TO RETROFIT MPS HANDLING MODULE

MPS is a modular production system that is widely used in engineering and automation education. CANopen and

OPC-UA are two communication protocols that can be used to upgrade the communication capabilities of the MPS handling module. Thus, Fig. 4.A compiles information regarding the communication protocols and the strategy used to acquire the data from the physical system of the module.

CANopen is a communication protocol that is used in industrial automation systems to connect various devices, such as sensors, actuators, and controllers. It is a standard protocol that allows devices from different manufacturers to communicate with each other in a common language.

By implementing CANopen in the MPS handling module, different devices can communicate with each other more efficiently and reliably, which can improve the overall performance of the system.

1) OPC-UA

OPC-UA (Open Platform Communications - Unified Architecture) is a communication protocol that is used to exchange data between different industrial devices and systems. It is a cross-platform, secure, and reliable protocol that can be used to communicate with devices from different manufacturers.

In the implementation of OPC-UA, it is possible to establish a secure and reliable connection between different devices and systems, which can improve the data exchange capabilities of the system.

The protocols used will be CANopen for horizontal integration of devices and OPC-UA for vertical integration of the system. CANopen is suitable for communication between devices on a factory floor network, while OPC-UA is a more suitable option for communication at a system level, allowing for the exchange of information between different layers and devices throughout the process.

In the proposed horizontal communication, after its update, the use of the CANopen network protocol will enable communication between the MPS handling module and the main controller that manages the entire production process.

The idea is that at least one module will be equipped with a microcontroller that supports the CANopen protocol to control specific functions and communicate with other modules and devices (sensors, actuators, controllers, and management systems). Communication between modules is carried out through CAN (Controller Area Network) messages, which are transmitted via the CAN bus. Each CAN message contains a unique identifier that allows the main controller to identify the module that sent it and the type of message being transmitted.

In the proposed vertical communication, the OPC-UA communication protocol will be used to integrate the layers of the proposed digital twin architecture. The idea is to use the protocol to transfer data between systems and to enable them to be controlled from a digital twin model.

The OPC-UA is a communication protocol that can be used to connect heterogeneous systems in an Industry 4.0 architecture. Its use provides standardized and secure connections of systems from different manufacturers and with different communication technologies.

Horizontal communication, using CANopen, is generally faster and more direct, with low latency and quick response time. However, vertical communication, using OPC-UA, allows for more open and secure communication between systems from different manufacturers but with potentially slower response times due to the complexity of the protocol and the need for authentication and security.

It is possible to use the OPC-UA protocol for web monitoring, which is a technology that allows users to access and monitor systems and devices remotely through an internet connection. In the context of MPS, web monitoring is a functionality that allows users to monitor and manage their industrial automation systems through a web browser.

2) EASYPORT

EasyPort is a connection interface that allows for quick and easy integration of Festo components into automation systems. It functions as an adapter that connects the components to a variety of electronic interfaces, including Ethernet, USB, CANopen, and Profibus. It allows for precise monitoring and control of these pneumatic components in real time through an external control system.

EasyPort is compatible with a wide range of Festo products, including cylinders, valves, sensors, and actuators, and it will be used as the gateway that connects one or more MPS modules to the application, which in this case will be CIROS, where the digital twin of the system will be implemented. Fig. 4b shows the methodology applied for the use of this approach.

EZOPC from Festo is a software tool that allows communication and control of components through an OPC (OLE for Process Control) connection. OPC is a widely used communication standard in the automation industry, allowing different control devices and systems to communicate with each other.

EZOPC works as an OPC server that connects components to an external control system, such as a PLC (programmable logic controller) or a SCADA (supervisory control and data acquisition). In this case, the application (CIROS) is an OPC client that communicates via the OPC protocol with EZOPC, which is an OPC server, and this, in turn, communicates with EasyPort, which is another OPC client.

Thus, EZOPC offers a user-friendly interface for configuring and programming communication between MPS components and the external control system. It also offers advanced features such as real-time data monitoring, event logging, and remote diagnostics.

V. RESULTS OF THE PROPOSED RETROFIT METHODOLOGY

The didactic platform of MPS V2.0 is considered a legacy system depending on the context in which it is used. Therefore, a legacy system is generally defined as a system that is old, outdated, or dependent on obsolete technologies (including software, hardware, or equipment) compared to the latest technologies available in the market.

When evaluating the results after the application of retrofitting in the MPS handling module, it was found that the platform used obsolete components and technologies that had already been replaced by more modern options. This fact justifies the classification as a legacy system.

It is important to note that the plant is a flexible and modular system that, despite some limitations, allows for the integration of new technologies and components. This means that it can be updated and adapted to meet the current production needs, aimed at the concept of I4.0. The update procedure used was described in the previous section.

Finally, FESTO regularly develops updates and improvements for the MPS system, which can help ensure that it remains relevant and up to date.

A. DESCRIBING EACH RETROFIT STEP APPLIED TO THE CASE STUDY

*Step 1:*The retrofit of the MPS handling module is the upgrade of the legacy system through the integration of current Industry 4.0 technologies into the process. This procedure involves updating/replacing sensors and devices and aims to achieve significant benefits in terms of efficiency, productivity, system lifespan, safety, and product quality.

*Step 2:*The MPS platform was acquired in 2011 and suffered from component degradation, sensor misalignment, defects or failures in actuators and other components. An aggravating factor is that the system was idle for a prolonged period without proper preventive maintenance, and this lack of use led to even further deterioration.

In the Handling Module, the claw's optical sensor is not properly fixed, the fiber optic and pneumatic hoses are deteriorated or broken, some electrical cables are disconnected, the input pneumatic actuator is misaligned, and the servo motor is functional, but its control driver has partial electrical connection, causing the conveyor to not be activated. The CPX-FEC PLC is functional, but its station control panel is not connected. Other electrical components are in good condition.

*Step 3:*The selection of components and technologies to be updated in a retrofit project is an important stage because it significantly impacts the project's success and must always be aligned with the objectives and goals of the retrofit process defined initially.

The activities realized in all modules are as follows:

- Cleaning and sanitizing the module and components.
- Organizing electrical connectors.
- Replacement of all pneumatic hoses.
- Replacement of the module controller.

Fig. 5.A shows the MPS handling module. The retrofit application at the conveyor station initially aimed to update and organize the module, replace some physical components, replace electrical and pneumatic connectors, and update the communication in the module through CANOpen where all I/O of the module is connected, allowing it to be connected, in the future, with a digital twin.

The main activities and modifications are the replacement and installation of the optical sensor fiber, the installation of the motor and its respective driver and finally a calibration of the pneumatic actuator.

The software version was updated to the last version to meet new demands, add new features, and fix issues. The module documentation, such as operation manuals and technical specifications, was updated to reflect the changes implemented in the module.

Step 4:

1) UPDATED HARDWARE

The CPX-CEC-C1-V3 is a controller designed for process automation systems. It is a compact, high-performance device that combines automation, communication, and human-machine interface functions in a single package. It is based on a high-speed microprocessor and has a variety of communication interfaces, including Ethernet, CANopen, and USB.

The controller has an intuitive user interface that allows for easy configuration and process monitoring. It can control various automation devices of the process, such as actuators, sensors, and other devices, through its communication interfaces. It can also be used to monitor device status and manage alarms and error messages. Finally, it has programming tools, such as IEC 61131-3, which allow users to easily program and modify the system's automation functions.

The CANopen network allows real-time monitoring and control of plant operations, as well as the configuration and programming of different devices and modules. The network is a safe and efficient option to ensure communication between the different elements of the smart factory and allows the integration of different automation technologies.

2) SOFTWARE UPDATED

CodeSys V3.5 is an integrated development environment (IDE) used for creating automation system applications, including programming, debugging, and testing. It is compatible with various hardware and software components and protocols, including CANopen.

The updated module already includes the production execution and management (MES) configuration, a type of software that helps manage and control production. It can be used for planning production, programming machines and equipment, controlling material and component inventories, monitoring production progress, and collecting data for analysis and optimization. In this implementation, MES can be used for managing the production of pneumatic and hydraulic components and equipment, as well as automation systems and motion solutions.

The implemented Web monitoring allows the remote monitoring of the process, enabling the visualization and analysis of data in real time through a web interface. This can be useful for the maintenance and optimization of systems, as well as for data-driven decision-making.

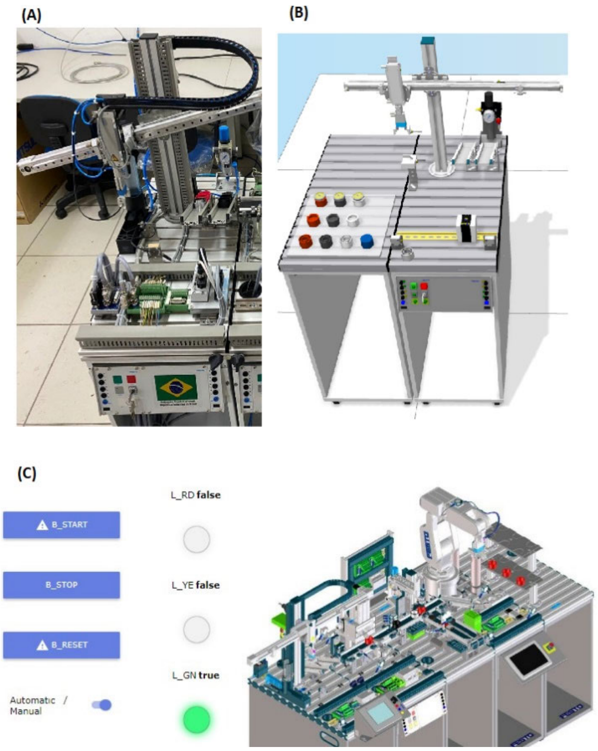


FIGURE 5. Results of Step 5 – Running the MPS handling module.

With Web Monitoring, users can view real-time information about the condition of devices, such as temperature, pressure, and load levels, as well as remotely configure and control the devices. This can include functions such as starting or stopping a process, changing device settings, or setting data alarms and limits.

*Step 5:*To ensure that the updated MPS handling module system operates according to specifications, it is crucial to test and validate the new components and technologies applied through the retrofit process.

Initially, it is verified if the new components and technologies are functioning according to specifications. Then, it is checked if they are integrated correctly into the system. At this stage, activation tests, operation cycle tests, and actuator movement tests will be performed.

The next step is to run a production script and test the functionalities, particularly of the actuators and sensors, finish tests, and inspection tests. The results are shown in Fig. 5.B

Validation ensures that the system is functioning correctly and that the new components and technologies are integrated properly. Therefore, after these steps, it is possible to confirm the compliance of the new components and technologies after the application of retrofitting on the MPS handling module, ensuring that the system is operating safely, efficiently, and reliably. Fig. 5.C shows the dashboard implemented to monitor and control the MPS handling module.

B. SIMULATION

CIROS Education offers various functionalities to teach and train the skills necessary to work in an industrial production environment. Some of the main functionalities include industrial process simulation, process control, robot programming, data analysis, team training, and simulation environment customization.

To establish communication between the updated module and CIROS Education systems, it is imperative to utilize an application consisting of an EasyPort that gathers data from the physical system and communicates with the virtual system through EzOPC.

Therefore, given that OPC-UA facilitates vertical communication in our process, it is feasible to designate the roles as follows: the updated system is connected to EasyPort and serves as an OPC client, while CIROS Education also functions as an OPC client. Meanwhile, EzOPC acts as the OPC server and is responsible for the communication interfaces with the physical and virtual systems.

Finally, with EasyPort, it is possible to connect multiple devices at the same time and monitor and control their state from a single access point. This allows for better system visibility and diagnostics and increases automation efficiency.

VI. CONCLUSION

Through the application of the retrofit methodology and digital twin architecture, as well as the use of communication tools, legacy systems can be modernized and optimized. This approach enables greater integration between systems and processes, real-time data collection and analysis, and improved decision-making and productivity.

In relation to the evaluation of Industry 4.0, it is possible to observe that the smart factory and the smart product have evolved significantly after the application of the retrofit methodology and digital twin architecture. Before the application of these technologies, the smart factory and smart product were in an early stage of maturity concerning the evaluation criteria of Industry 4.0. After the application of these technologies, the smart factory and smart product have reached higher levels of maturity and advanced toward a smarter factory and product.

The successful application of the digital twin methodology and architecture enables the adaptation of legacy systems to the principles of Industry 4.0, resulting in significant improvements in production efficiency and productivity.

This ability to update obsolete systems and make them more competitive in a digital transformation scenario is a crucial benefit of this process, allowing companies to benefit from the latest technologies and meet market demands more efficiently.

For future works, the goal is to use an application for digital twins to enable the simulation of the system's behavior across various operating conditions, thereby facilitating performance optimization without the necessity of physical prototyping or testing. Therefore, we propose archive results such as streamlining the product development process, minimizing testing requirements, and optimizing performance while reducing both time and cost expenditures.

Utilizing the EasyPort technology for data collection with the CIROS Education platform proves to be a highly effective method for creating a virtual representation of physical systems or products that will be used in digital twins. The integration of EasyPort and CIROS Education serves as a foundation for constructing an accurate digital twin that can facilitate, for example, a better analysis and improvement of system performance.

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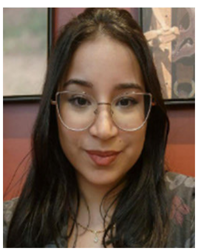

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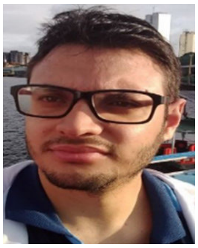

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