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VIRTUAL PROTOTYPING AND IMPLEMENTATION OF A PLC-BASED SORTING LINE USING DIGITAL TWIN SIMULATION IN FLEXSIM

Adrian Kampa[1], Piotr Michalski[2]

[1,2]Silesian University of Technology, Mechanical Engineering Faculty, Department of Automation of Technological Processes and Integrated Manufacturing Systems, Konarskiego 18a, 44-100 Gliwice, Poland

Corresponding author: Adrian Kampa, adrian.kampa@polsl.pl

***Abstract*:** Programmable logic controllers (PLC) are a main part of modern automated manufacturing systems. However, PLC programming presents a number of technical, organizational, and competency challenges. Therefore, the purpose of this article was to build a framework for virtual prototyping of PLC-based control systems in the FlexSim simulation environment, in accordance with Simulation Model-Based Systems Engineering (SMBSE). This work includes an example of conceptual design of a disassembly station and goes through the application of SIL (Software-in-the-Loop) and HIL (Hardware-in-the-Loop) methods and the Digital Twin of an automated sorting line. Expected results include the implementation of a prototype sorting line that will ensure sorting accuracy and efficiency. A working prototype of a sorting line based on an S7-1200 series PLC and a conveyor belt is also presented, together with conclusive remarks, including achieved sorting accuracy higher than 91.6%
***Key words*:** Digital Twin, PLC-Programmable Logic Controller, Modern Manufacturing, and Virtual Prototyping

1. INTRODUCTION

In an era of dynamic development in industrial automation, PLCs (Programmable Logic Controllers) remain the foundation of modern control systems in smart factories and Industry 4.0 [1, 2]. From simple machine control applications to complex manufacturing and infrastructure processes, PLCs are an indispensable tool for engineers and automation specialists. Their flexibility, reliability, and ability to operate in harsh industrial environments make them used in virtually every industry: from energy and automotive to pharmaceuticals and food production. Supporting a variety of communication protocols and integrating with SCADA, MES, and IIoT systems, PLCs not only perform control tasks but also serve as intelligent data hubs in distributed production systems [3, 4]. Contemporary PLC solutions increasingly combine traditional automation approaches with modern digital technologies, enabling predictive maintenance, real-time data analysis, and remote process management [1, 5]. PLC programming, while the foundation of modern industrial automation, presents a number of technical, organizational, and competency challenges. A key aspect is the need to precisely represent the logic of the technological process in a programming language compliant with the IEC 61131-3 standard [6, 7], which requires not only knowledge of programming structures (e.g., LD, FBD, ST) but also a deep understanding of the process physics, its dynamics, and safety requirements. PLC programming encompasses, among other things, scanning cycle management, synchronization with peripheral devices, handling analog and digital signals, as well as integration with supervisory systems (SCADA, MES, ERP). In the context of Industry 4.0, ensuring program reliability and resilience to both logical errors and those resulting from disruptions in the industrial environments is also a significant challenge. Therefore, PLC programming is an interdisciplinary engineering practice requiring continuous improvement and adaptation to changing technologies [8]. This article discusses the virtual prototyping of PLC-based control systems in the FlexSim simulation environment, starting with conceptual design and continuing through the application of SIL (Software-in-the-Loop) and HIL (Hardware-in-the-Loop) methods and the Digital Twin of a sorting line. Based on the simulation model, a digital twin of the real system can be built, as with the direction of information flow reversed, now the controller sends signals from the outputs to the simulation environment based on input signals from real sensors placed on the line.
A prototype for a sorting line based on an S7-1200 series PLC and a conveyor belt is also presented, together with conclusive remarks.

2. MATERIAL AND METHODS

A process for designing a station for disassembling and sorting parts of varying quality, a significant number of which can be reused, is being considered. The loudspeaker production process involves several defective products that are only revealed after final testing (e.g., burned-out coils, detached diaphragms, etc.). The problem also

applies to the disassembly and repair of defective products returned by customers under warranty. Considering the principles of the green economy, such as the 3Rs (reduce, reuse, recycle), the priority is to reduce waste production (reduce), reuse items (reuse), and then recycle materials (recycle) [9]. Therefore, manual disassembly of defective products is performed to recover parts such as magnets and housings, which can then be reused in the assembly process. While the assembly process itself is designed according to DFA (Design for Assembly) principles, which significantly simplify assembly, the disassembly process is complicated by the use of glued, soldered, and press-fit connections. Due to the disassembly of various types of loudspeakers of varying sizes, the disassembly process is subject to significant variations depending on the employee's experience and the presence of defects. Disassembly is also characterized by varying amounts of recovered components, which are then sorted. Because human error is a significant factor during sorting, it was decided to design an automated line for sorting parts from disassembly. Therefore, the main optimization criterion is the sorting accuracy, which can take values from 0 to 100%. The expected accuracy of automatic sorting was assumed to be above 90%.
Figure 1 shows the concept of a disassembly station with an automated sorting line controlled by a PLC controller.

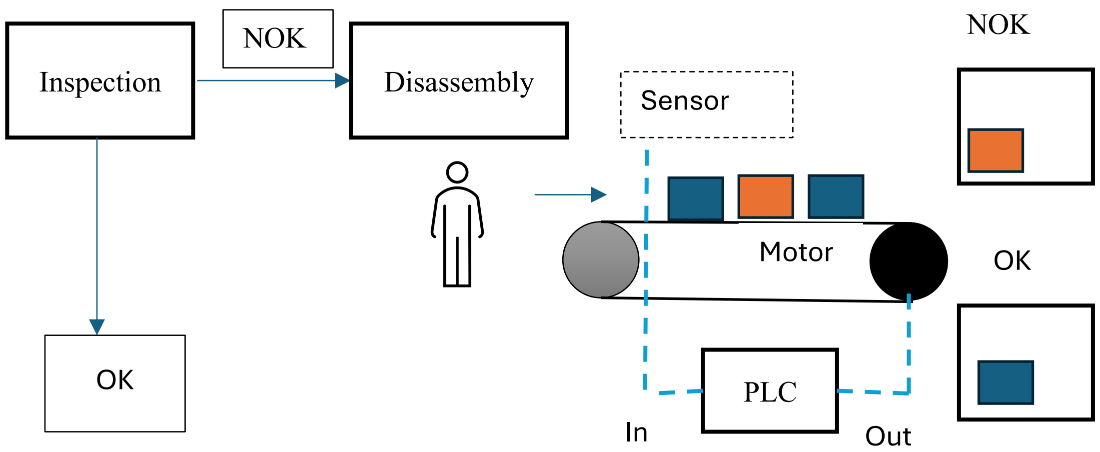

Fig. 1. The concept of a disassembly station and an automatic parts sorting line

It was assumed that this line would operate based on a conveyor belt and a PLC controller that processes signals from sensors (e.g., photocells) and controls output devices (actuators) [10]. At the initial stage, it was assumed that two types of parts of different sizes would be segregated, divided into small and large, which could be in two color versions: light and dark.

2.1. Theory and methodology

The design methodology is based on the gradual refinement of the adopted concept based on design assumptions and the technical specifications of the implemented technical means, in accordance with Simulation Model-Based Systems Engineering (SMBSE) [11]. This engineering approach combines classical modeling principles with dynamic system simulation using Software-in-the-Loop (SIL) and Hardware-in-the-Loop (HIL) methods [12, 13]. Its goal is to enable the integrated, model-based design, analysis, and validation of complex systems before their physical implementation. Diagrams of both methods, together with the digital twin, are shown in Figure 2.
To streamline the conceptual design and programming of PLC control system logic, discrete process modeling and simulation in FlexSim 2024 with the Emulation module were used, combined with parallel PLC programming in the Siemens TIA Portal v19 environment using the PLCSim Advanced v6 virtual controller. This approach aligns with the SIL method. This method of testing and validating PLC control software allows the controller code to be run in a simulation environment without the need for physical hardware. The entire system, both the controller and the control object, is simulated in software. Using controller emulation in FlexSim and real-time communication with the virtual controller, it is possible to emulate the PLC's input and output signals, significantly streamlining program development and verification. This allows for early detection of logical errors, testing of control algorithms, and analysis of system behavior in various operating scenarios.
Next, a physical S7-1200 controller was used, working with the simulated system in the FlexSim 2024 environment. Programming PLCs using HIL is an advanced engineering approach that allows for testing and validating control code in near-real-world conditions, even before its implementation in a physical installation. In the classic PLC programming model, testing takes place on a real object, which carries the risk of errors, downtime, or hardware failure. The HIL method eliminates these risks by enabling the connection of a real PLC

with a virtual model of the technological process. In practice, this means that the PLC executes its program as if it were controlling a real object, but instead of physical input/output signals, it communicates with a process simulation model [12, 13]. This allows for real-time testing of control logic, taking into account process dynamics, and verification of response to emergencies. It also allows for accelerating the design cycle through parallel software and hardware development and optimization of control algorithms without the risk of interfering with the live production system [14].

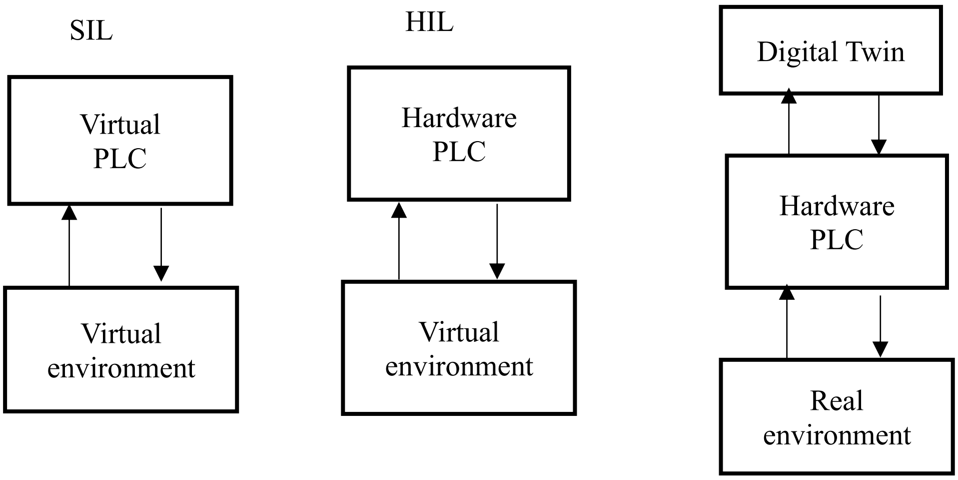

Fig. 2 Diagrams of SIL, HIL, and Digital Twin methods

Based on the developed simulation model, a Digital Twin can also be built [15, 16]. Because the communication between the PLC controller and the digital twin model is like that in the HIL method, but with the direction of information flow reversed, the controller can now send signals from the outputs to the simulation environment based on input signals from real sensors placed on the line.

3. RESULTS AND DISCUSSION

In the first stage of the project, a conceptual model was developed in the FlexSim 2024 environment, shown in Figure 3. The model included both the assembly processes of several product versions and the process of inspection and disassembly of defective products.
The right side of Figure 3 shows a model of the parts sorting line, which underwent further design work. This model allows for the synchronization of production processes and the integration of ongoing production processes [16, 17]. Next, the sorting process control logic was developed using the Process Flow programming language with an Internal Server Connection, as shown in Figure 4.

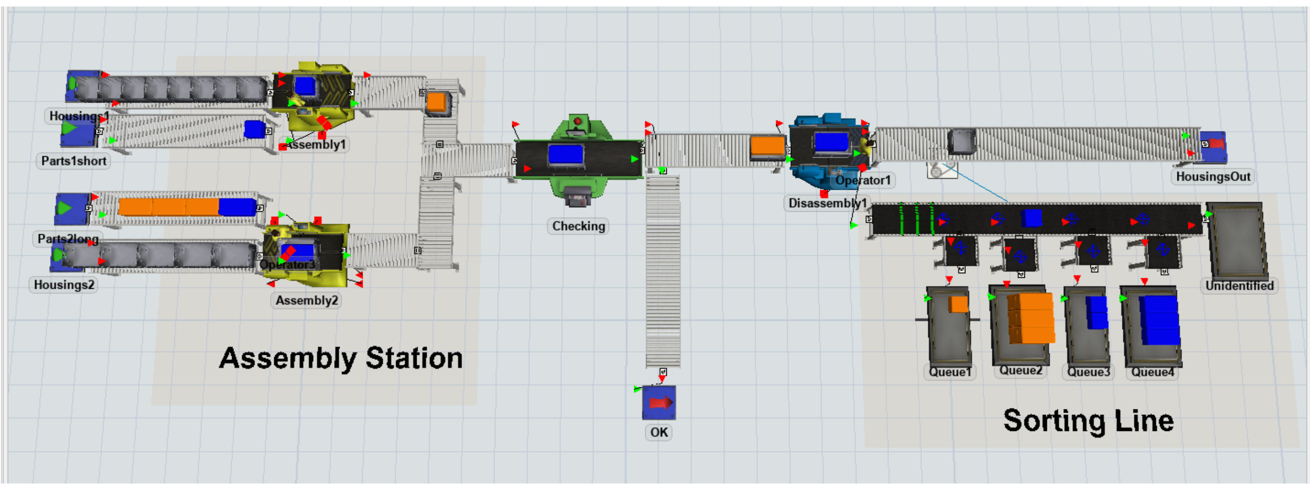

Fig. 3. Conceptual model of the assembly and disassembly system and the automatic sorting line.

In the next step, the entire control logic for the sorting process was transferred to a virtual PLC using the TIA Portal v19 and PLCSim Advanced v6 environments. First, the software was tested in local host mode on a single workstation using the PLCSIM transmission protocol, which enabled the PLC logic to be verified and errors to be resolved.

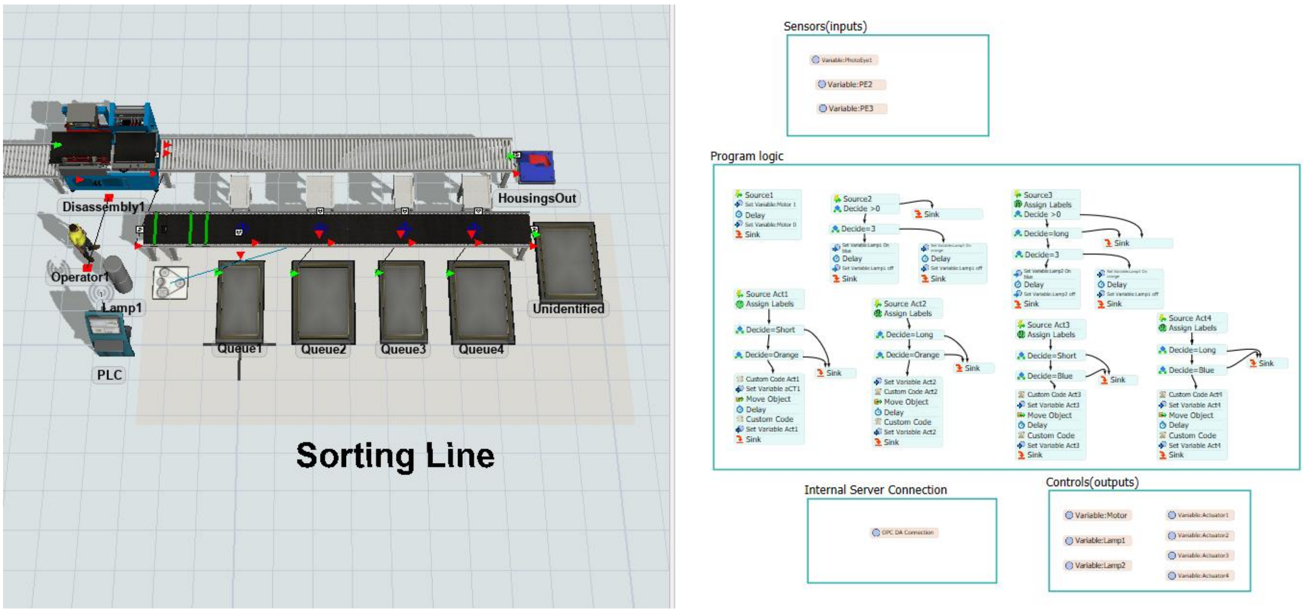

Fig. 4. Detailed model of the sorting line with internal control logic in Process Flow

Next, the modeled system was tested using a TCP/IP internet connection on two computers in a local network using the Siemens S7 transmission protocol. The Flexsim 2024 simulation environment was run on one computer, and the virtual PLCSim controller was run on the other. The Siemens S7 communication protocol was used, enabling data exchange between SIMATIC S7 series PLCs and external devices, HMI operator panels, and SCADA systems. The tests confirmed the program's correct operation in the simulated environment, which is described as virtual prototyping or Virtual Commissioning [3]. Although the virtual prototype (after eliminating errors) achieved 100% sorting accuracy, some technical issues may arise during physical implementation, which are described in the next section.

3.1. Development of a prototype of an automated sorting line

Based on the experience gained, we began building a small-scale physical prototype. Due to limited resources, some design changes were made to minimize the design. The fully functional prototype of the sorting line, constituting a Proof of Concept (PoC), is shown in Figure 5.


Fig. 5. Functional prototype of the sorting line

Adopting the general principle of safe design of prototype machines, guidelines were established for three main flows: energy flow, matter flow, and information flow. Three modules were designed for the energy flow: a 230VAC power supply distribution module (for the three-phase asynchronous motor inverter, which serves as the main conveyor belt drive), a 24VDC power supply distribution module for the control system, and a compressed air distribution preparation module (for operating the electropneumatic valves used to discharge components from the conveyor belt to the warehouses).

The material flow is presented as a conveyor belt system, carrying model blocks of two different dimensions and two different colors (blue and orange). Additionally, the blocks are equipped with RFID tags enabling individual

object identification. According to the design, the system is activated when a randomly selected block is placed at the beginning of the line. As the conveyor belt moves, it allows sensors to conduct an inspection, determining the component's length, color, and RFID tag number. Correct identification allows the component to be redirected to the appropriate container, simulating a disassembly station. The information flow is represented by a series of parameters determined by the integrated industrial sensors. These parameters are collected by a Siemens S7-1200 controller system and process parameter acquisition modules in the form of IO-Link masters from the AL1306 series from ifm electronic. The station allows for the collection of information regarding conveyor belt speed, the path traveled by the block, the precise RGB color parameters of the block, the longitudinal dimensions of the block, the number of blocks in warehouses 1-4, and the amount of unidentified waste. Using the Profinet network, it is possible to smoothly control the start and stop ramps of the gear motor connected to the conveyor belt drive shaft, as well as to freely direct the information flow and control the material flow as needed.
While the virtual prototype achieved 100% sorting accuracy, during implementation, we encountered some problems with color sensor calibration. The tests carried out showed the need to modify the actual system, both in terms of its structure and control system. Improvements made include the correct installation of the color sensor (to eliminate external light reflections), which results in an improvement of sorting accuracy and reduces the conveyor belt speed in order to increase the scanning time of the sensor, which results in a slight reduction in sorting efficiency. Ultimately, we achieve sorting accuracy higher than 91.6% (maximum 1 unidentified piece per batch of 12 pieces), which constitutes proof of concept.
A further step was to develop a digital twin model of the sorting line, shown in Figure 6, which faithfully reproduces the operation of the real system.

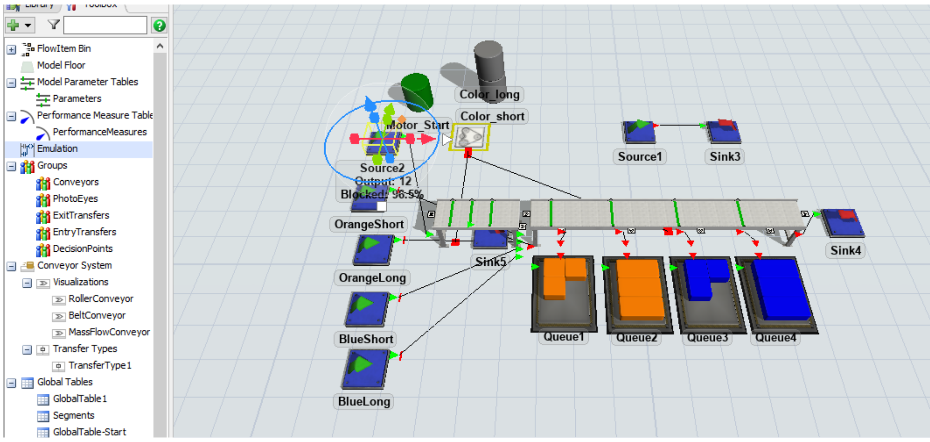

Fig. 6. Digital twin model of the sorting line in FlexSim 2024

Communication between the PLC controller and the digital twin model is similar to the HIL method, but with the direction of information flow reversed, because now the controller sends signals from the outputs to the simulation environment based on input signals from real sensors placed on the line.

4. CONCLUSIONS

The project activities confirmed the usefulness of SIL and HIL methods during the virtual prototyping of the PLC control system in the FlexSim simulation environment. This allows for real-time testing of control logic, taking into account process dynamics, and verification of response to emergencies. It also allows for accelerating the design cycle through parallel software and hardware development and optimization of control algorithms without the risk of interfering with the live production system.
While the virtual prototype achieved 100% sorting accuracy, we encountered some problems with color sensor calibration during implementation. Improvements made include the correct installation of the color sensor (to eliminate external light reflections), which results in an improvement of sorting accuracy and reduces the conveyor belt speed in order to increase the scanning time of the sensor. Ultimately, we achieve sorting accuracy higher than 91.6% (maximum 1 unidentified piece per batch of 12 pieces), which constitutes proof of concept.
Further improvements are planned to increase sorting accuracy and efficiency and to include the creation of a full-scale installation for the sorting and reuse of disassembled parts and the expansion of the simulation model of a digital twin of the sorting system, based on Control-in-the-Loop (CIL) communication between the PLC and the simulation model. This will enable the digital twin model to replicate the behavior of the real system based on signals transmitted by the PLC while also drawing on signals from real sensors located on the line and dynamic modification of PLC parameters through Digital Twin.

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