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DESIGN AND IMPLEMENTATION OF A PLC-BASED CONTROL SYSTEM FOR A FLEXIBLE MANUFACTURING CELL

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ABSTRACT

In the context of the accelerated development of industrial automation and the increasing requirements for flexibility and efficiency of production processes, flexible manufacturing systems represent a modern solution for integrating machine tools, transport systems, and assembly equipment, supporting digital twin and real-time monitoring approaches [29-30]. This paper presents the design and implementation of a control system based on a programmable logic controller (PLC) for a flexible manufacturing cell comprising two CNC machines and a subsystem dedicated to the assembly of finished products.

In the first part of the paper, the general structure of the system is presented, identifying and describing the component subsystems: the raw material transport subsystem, the parts reception, processing and evacuation subsystem, the semi-finished product transport subsystem and the assembly subsystem. For each of these, the functional role, the hardware elements used and the interactions between the subsystems are analysed. The manufacturing process is detailed in stages, from sorting and feeding CNC machines to assembling and counting finished products.

A central aspect of the work is the modelling of the system's operating logic in the form of a finite automaton, by defining the inputs, outputs and states corresponding to each subsystem. State transition graphs are presented and how they ensure process synchronization, deadlock prevention and safe operation of the manufacturing cell.

The simulation of the system's operation was performed using the Factory I/O software, through the Control I/O driver, which allows the development of control logic using functional blocks specific to real PLCs. The simulation allowed testing the system's behaviour in various operating scenarios and validating the proposed solution, without the risks associated with physical implementation.

The results obtained confirm the correct and stable operation of the designed control system, highlighting the advantages of using industrial simulation in the design and training process. The presented solution can constitute a basis for further extensions, such as the integration of advanced control strategies, monitoring systems or manufacturing process optimization functions.

Keywords: PLC, flexible cell, manufacturing system, Factory I/O, digital twin

INTRODUCTION

The accelerated development of industrial technologies, combined with the ever-increasing demands on productivity, flexibility and quality of manufacturing processes, has led to a significant increase in the degree of automation in the modern industrial environment. Flexible manufacturing systems represent an effective solution for rapid adaptation to production variations, allowing rapid adaptation to production variations and integration with intelligent monitoring frameworks [29],[31].

In this context, the use of programmable logic controllers (PLCs) plays an essential role in the management and coordination of complex industrial processes. PLCs ensure reliability, precision and the possibility of implementing advanced control strategies, being widely used in applications involving CNC machines [9],[32],[33], transport systems, industrial robots and assembly lines.

The present work aims to design and implement a PLC-based control system for a flexible manufacturing cell, consisting of two CNC machining centres and an assembly subsystem. The proposed approach includes the structural analysis of the system, the identification of the component subsystems, the definition of inputs, outputs and states, as well as the modelling of the process in the form of a finite state machine. Simulation environments such as Factory I/O enable validation of control strategies and virtual commissioning, in line with recent digital twin methodologies [3],[9],[15],[33].

The theoretical foundations of the organization and management of flexible manufacturing systems are presented in reference works such as the course support dedicated to the management of flexible systems [4], which highlights the importance of structuring industrial processes into functional subsystems and coordinating them through hierarchical control systems. An essential role in these systems is played by programmable logic controllers, used to manage sequential and discrete processes. The architecture of microprocessor systems and their operating principles are detailed in classic works in the field [4], which substantiate the use of PLCs in complex industrial applications. The integration of industrial robots into such systems is addressed in works dedicated to manipulator robots and their management [1],[2],[16], which describe the kinematic structure, types of actuations and the role of sensors in achieving automatic handling of parts.

Computer numerically controlled (CNC) machine tools are a central element of modern manufacturing systems, and numerous studies focus on improving their performance. Works such as [6],[16] and [23] deal with the programming and operation of CNC machines, providing a solid practical basis for their integration into flexible manufacturing cells. In parallel, recent research focuses on the development of advanced control and diagnostic methods. For example, the use of adaptive control and hybrid PID–fuzzy techniques to improve the performance of CNC machines is analysed in [6],[18],[19], highlighting the advantages of these methods under variable operating conditions.

Intelligent fault diagnosis and condition monitoring of CNC machines is an important research direction, with direct applications in increasing reliability and reducing downtime. Various approaches based on expert systems, case-based reasoning and data analysis have been proposed in the literature [21],[22],[28],[31]. Studies [17],[20],[25],[30], propose various approaches based on expert systems, case-based reasoning and fault simulation, demonstrating the need for a control system capable of managing multiple states and reacting quickly to the occurrence of anomalies.

The accuracy and reliability of machining processes are analysed in works that deal with positioning errors, equipment degradation over time and their compensation methods [10-14]. The studies presented in [8],[20] and [27] emphasize the importance of evaluating uncertainties and operational reliability, aspects that justify the need for rigorous control of industrial processes and correct synchronization between component subsystems.

In a broader context, research on advanced manufacturing technologies and the impact of the new industrial revolution is discussed in [30], where the transition towards intelligent, integrated and digitalized production systems is highlighted. These directions are supported by the use of simulation environments and virtual factories, which allow testing and validation of control solutions before physical implementation. Although the specialized bibliography covers these issues in detail, technical resources and online documentation [32-36] provide practical support for the actual implementation of automated systems and for the configuration of components used in simulation [5],[7].

In this context, the present work aligns with the current state of research, proposing an integrated approach to control a flexible manufacturing cell, based on PLC and validated through industrial simulation [2],[24],[26]. PLC-based systems are increasingly coupled with intelligent control and IoT-based monitoring to ensure high efficiency and flexibility [3],[15],[23]. The contribution consists in the clear modelling of the process in the form of a finite automaton and in the demonstration of the coherent operation of the system in a simulation environment close to industrial reality, providing a solid basis for further developments.

This PLC-based approach validated through industrial simulation is particularly relevant to the oil and gas industry, where increased flexibility, reliable operation, predictive diagnostics, and integration with IoT/digital-twin systems can reduce downtime, enhance safety, and optimize production costs.

FLEXIBLE MANUFACTURING CELL HARDWARE DESIGN

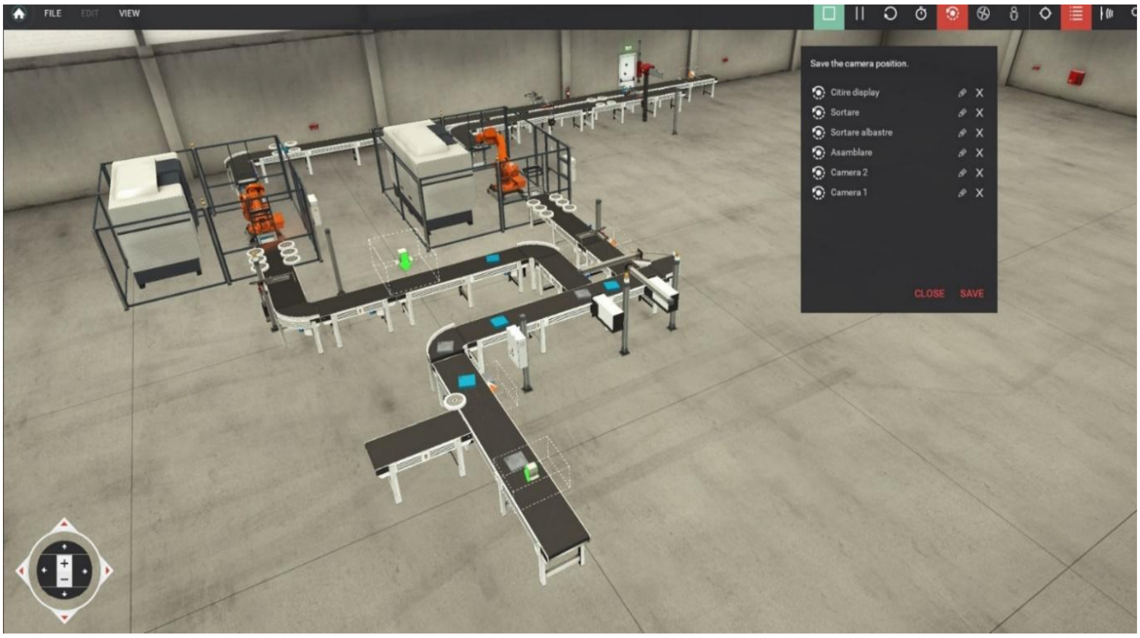
To design the control of the flexible system, it is necessary to specify its component elements and the mode of operation. The flexible manufacturing system is composed of the following elements: CNC1 and CNC2 processing machines, each responsible for separate processing of different raw materials; one machine to assemble the two semi-finished products from the two processing machines; conveyor belts for the raw materials to the two processing machines; actuators (pushers) that push the raw material from the raw material conveyor belt to the two processing machines depending on the type of raw material accepted by each machine; conveyor belts for the two semi-finished products to the assembly machine; digital display to display the number of successfully assembled finished parts.

The raw material conveyor belt ensures the flow of raw material to the two processing machines. The operation of this belt is continuous and the selection is made by activating the actuator next to each machine when the sensors detect the corresponding type of raw material (blue or metal, as will be defined in the application).

The two machines are equipped with sensors at the entrance that detect the presence of raw material, thus giving a signal for the takeover and processing of the part. The CNC machines are also equipped with sensors that limit the stroke of the robotic arm, indicate the operational status, and monitor the position of the door (open or closed). Additionally, a sensor is installed at the exit of each CNC machine to detect the discharged workpiece.

The conveyor belts of the semi-finished products from CNC1 and CNC2 to the assembly machine have a discontinuous operation, conditioned by the number of parts discharged by each machine and present on the discharge belt to ensure a constant flow of each type of semi-finished product and the assembly machine will not block.

For example, if there are two blue blanks and no grey-coloured blanks, the blue conveyor will block one of the two blue blanks waiting for the arrival of a grey-coloured blank. After the grey-coloured blank has arrived and the finished product is assembled, the blocked blue blank is released and a new grey-coloured blank is waited for final assembly, and so on. Figure 1 shows the layout plan of the described system, made using Factory I/O technology.



Save the camera position.

***Figure 1**. System layout (Factory I/O)*

The flexible system has the following component: the command-and-control subsystem; the part reception/processing/ejection subsystem; the raw material transport subsystem; the semi-finished and finished product transport subsystem; the finished product assembly subsystem.

Transport subsystem is responsible for transporting raw materials from the source to the input of CNC1 and CNC2 processing machines as well as semi-finished products from the processing machines to the assembly machine. It contains conveyor belts, sensors for detecting and identifying the type of raw material, actuators (pushers) to direct the raw material to the appropriate processing machine, sensors for detecting presence on the belt. Automated transport and assembly subsystems now benefit from advanced sensors and communication protocols, improving interoperability and real-time control [32].

Conveyor belts. They operate continuously and are either straight or curved in shape. Also known as conveyors, they are mechanical systems used to transport materials or objects from one point to another. They are essential in various industries, from manufacturing and logistics to airports and distribution centres.

There are various categories of conveyor belts, each designed for specific uses. For the implemented system, belt conveyor belts, either straight or curved, were considered. Straight conveyor belts are the most common and are used to move materials on rectilinear paths. They are perfect for production lines where materials need to be moved over long distances without changing direction. Curved conveyor belts, on the other hand, are designed to move materials on paths that require changing direction. They are essential in confined spaces or in complex arrangements. Figure 2a shows a straight conveyor belt and Figure 2b shows a curved conveyor belt.

Figure 2. *a) Straight conveyor belt* [16], *b) Curved conveyor belt* [12]

Sensors used for detection on the belt are diffuse photoelectric sensors but also retroreflective photoelectric sensors. A diffuse photoelectric sensor, also known as a diffuse-reflective sensor, works by emitting a beam of light from an emitter. This beam of light travels towards an object and is then reflected to a receiver located in the same housing as the emitter. At the moment of detection, a signal will be generated that can be used to activate or deactivate certain elements in the process. A retroreflective photoelectric sensor works by emitting a beam of light from an emitter to a special reflector. The light reflected by this reflector is then captured by a receiver located in the same housing as the emitter.

Pusher is a mechanical device used in various industrial applications to move objects along a specific path. Such a device is shown in Figure 3.

Part receiving / processing / ejection subsystem. It is responsible for ensuring the detection of objects at the CNC input, the correct pickup of the raw material using the robotic arm and its introduction into the processing machine. After the processing has been successfully completed, the semi-finished part is picked up again by the robotic arm and discharged. This subsystem ensures that the part has been discharged successfully by means of the presence sensors used at the CNC output. The subsystem is composed of raw material detection sensors at the CNC input; robotic arm for picking up parts; CNC machine; Semi-finished part detection sensors at the CNC output; Sensors for determining the status of the CNC machine.

Sensors used in this subsystem are like those described previously.

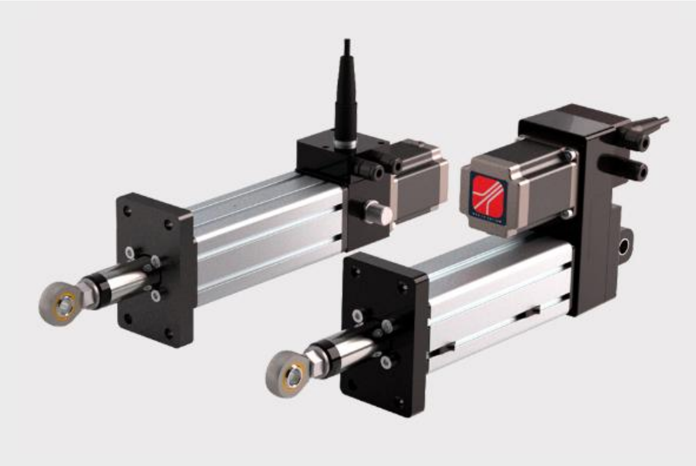


***Figure 3**. Industrial pusher* [14]

Robotic arm used for material handling is an essential element in the simulation of industrial processes. It is used to move and position objects in various locations on the production line. The robotic arm is controlled by a PLC that defines its movements and actions, and programming is done using Ladder Logic or Function Block Diagram. To perform tasks, it uses sensors to detect the presence and position of objects. These sensors can be photoelectric, inductive or capacitive, depending on the application. It is also equipped with a gripper that grips the objects. The gripper can be pneumatic, electric or hydraulic, providing a safe and precise grip. The robotic arm moves according to programmed instructions, using motors and actuators to perform the necessary movements. It can perform linear and rotary movements, allowing it to reach various locations. Objects are precisely positioned in the desired locations, the robotic arm releases the grip and retracts to its original position, ready for the next cycle. Figure 4 shows a screenshot from Factory I/O highlighting the part receiving / processing / ejecting subsystem.

***Figure 4**. Part reception / processing / ejection subsystem (Machining center) (Factory I/O)*

Finished product assembly subsystem is responsible for ensuring the correct assembly of the semi-finished products coming from the two CNC machines. Following the processing, two types of semi-finished products result which are discharged on two different conveyor lines.

When the sensors detect the presence of both types of semi-finished products, they will be assembled in the order established by the program. For assembly, a robotic arm with linear coordinates is used, which allows movements on two axes. The robot aligns and assembles the covers and bases together and the assembled parts are then transferred to the next stage of the production line. The two-axis system allows the robot to move in two directions, usually horizontally and vertically, to pick up and place the parts with precision. The sensors used to detect the presence and position of the parts, ensuring precise assembly were presented in the previous subchapters. The gripper with which the robot is equipped has the role of gripping and manipulating the parts during the assembly process. Figure 5 shows a screenshot from Factory I/O with such a robotic arm for assembly, equipped with the necessary sensors and gripper.

***Figure 5**. Robotic arm for assembly, with 2-axis movement (Factory I/O)*

OPERATIONAL PHASES AND PROCESS DESCRIPTION

According to the subsystem organization of the implemented system, the operating phases that make up the process can also be described as a collection of sub-phases and stages.

Stage 1 is the phase where the raw material is transported and sorted so that each CNC machine is fed with the appropriate type of material.

- The raw material is transported by conveyor belts to the sensors that recognize the type of material. If the material is recognized by the sensor, the corresponding pusher is activated, and the object is pushed towards the CNC machine.
- After sorting, on the way to the associated CNC, the objects pass through proximity sensors with the help of which the objects are counted. To avoid overcrowding at the CNC entrance, there are barriers on the conveyor belt that will stop the passage of the material, and the pushers will not sort until the belt is released.

Stage 2 is related to the receipt, processing and disposal of semi-finished parts.

- The raw material arriving at the CNC input will obstruct the sensor's light beam, which will cause the CNC machine to start the object pickup sequence: the robotic arm rotates 90° to the left, the gripper will close, picking up the piece, and then placing it in the machining machine.
- The protective door will close and machining will begin, with the CNC status becoming active.
- After the processing is completed, the door will open, the robotic arm will take the processed part from inside, rotate 90° to the right, placing the part on the exit ramp.

Stage 3 is the phase in which the transportation of semi-finished parts and their assembly take place.

- After being ejected, the part will pass through another proximity sensor which, generating a signal, will count the ejected parts present on the belt. This is necessary to avoid overcrowding the assembly machine entrance.
- The semi-finished product that arrives at the assembly machine is recognized and detected by sensors. Depending on the type of semi-finished product that arrives first at the assembly machine, its state differs. Thus, if the base semi-finished product arrives first, the machine remains in the waiting state. Otherwise, if the cover semi-finished product arrives first, the machine will grab the part and wait for the complementary part to arrive.
- If both types of materials are present, then the assembly machine will go into the active state and assemble them.
- After correct assembly, the sensors will detect this and raise the automatic barrier. The finished product passes through a proximity sensor which will cause the stored value of the semi-finished products on the belt to decrement.

DESIGN OF THE SYSTEM CONTROLLER

Starting from the five identified subsystems, namely: the command and control subsystem, the raw material transport subsystem, the part reception/processing/ejection subsystem, the semi-finished and finished product transport subsystem, and the finished product assembly subsystem, we can deduce that the output and state of a system located, from a logical and functional point of view, before another influences the input value and state for the latter, but also vice versa.

To support the previous statement, we can provide a concrete example: if the part receiving subsystem is in the "Waiting for Raw Part" state, the raw material transport subsystem will be in the "Active" state, meaning that upon detecting the first object of the type of material sought, the pusher will push the object to the corresponding CNC machine. Conversely, if the part receiving subsystem is in the "Take_raw_part_from_the_CNC_input" state, the raw material transport subsystem will go into the "Idle" state, meaning that upon detecting the corresponding type of material, it will no longer be directed to the CNC machine in order not to overcrowd its input and avoid blocking the process.

To establish the shape of the state graph, it is necessary to identify the inputs, states, and outputs of the subsystems of the implemented system. The system implementation was carried out using the Factory IO simulation program, which offers both hardware and software simulation facilities, having its own PLC simulator, called Control IO.

The manufacturing process was adapted according to the simulator's capabilities and involves the parallel processing of two different types of raw material. On one of the lanes, bases (referred to as "base" in Factory I/O) made of blue raw material and covers (referred to as "lids" in Factory I/O) made of grey-coloured raw material are processed.

After processing these 2 types of semi-finished products, they are assembled using an assembly machine and sent to the packaging area, the packaging process not being addressed within the application.

Entries system is the following:

I0 – Start Button
I1 – Stop Button
I2 – Blue raw material detection sensor
I3 – Grey-coloured raw material detection sensor
I4 – Presence sensor on blue raw material conveyor belt
I5 – Presence sensor on grey-coloured raw material conveyor belt
I6 – Raw material presence sensor at CNC1 input
I7 – Raw material presence sensor at CNC2 input
I8 – CNC1 robotic arm stroke limit sensor 90o left
I9 – CNC2 robotic arm stroke limit sensor 90o left
I10 – CNC1 robotic arm stroke limit sensor 0o
I11 – CNC2 robotic arm stroke limit sensor 0o
I12 – CNC1 robotic arm stroke limit sensor 90o right
I13 – CNC2 robotic arm stroke limit sensor 90o right
I14 – Blue blank presence sensor at CNC1 output
I15 – Grey-coloured blank presence sensor at CNC2 output
I16 – Blue semi-finished product presence sensor at the assembly machine
I17 – Grey-coloured semi-finished product presence sensor at the assembly machine
I18 – Finished product presence sensor on the counting belt
I19 – Blue base detection sensor on line 2 awaiting assembly
I20 – Lid detection sensor correctly mounted on line 2 above the blue base
I21 – Grey-coloured cover detection sensor on line 1 waiting for assembly
I22 – Sensor for detecting the grip/release of the lid for assembly
I23 – Sensor for position on the Ox axis of the assembly machine (false for x = 0 and true for x = xmax)
I24 – Sensor for position on the Oz axis of the assembly machine (false for z = 0 and true for z = zmax)
I25 – Sensor for the closed / open position of the positioning system on the grey-colored semi-finished product conveyor belt (line 1)

The system outputs are as follows:

O1 – Transport conveyors (On: O1=1, Off: O1=0)

O2 – Pusher 1 blue material (On: O2=1, Off: O2=0)

O3 – Pusher 2 grey-coloured material (On: O3=1, Off: O3=0)

O4 – Automatic barrier on the blue raw material conveyor belt raised / lowered (Up: O4=1, Down: O4=0)

O5 – Automatic barrier on the grey-coloured raw material conveyor belt raised / lowered (Up: O5=1, Down: O5=0)

O6 – CNC1 robotic arm moves left 90o, picks up the part (true: O6=1, false: O6=0)

O7 – CNC2 robotic arm moves left 90o, picks up the part (true: O7=1, false: O7=0)

O8 – CNC1 robotic arm moves straight 90o to return to 0, deposits the part for processing (true: O8=1, false: O8=0)

O9 – CNC2 robotic arm moves straight 90o to return to 0, deposits the part for processing (true: O9=1, false: O9=0)

O10 – CNC1 processes the part (true: O10=1, false: O10=0)

O11 – CNC2 processes the part (true: O11=1, false: O11=0)

O12 – CNC1 robotic arm moves straight 90o, deposits the machined part (true: O12=1, false: O12=0)

O13 – CNC2 robotic arm moves straight 90o, deposits the machined part (true: O13=1, false: O13=0)

O14 – Automatic barrier 1 on the blue semi-finished product conveyor belt (line 2) raised / lowered (Up: O14=1, Down: O14=0)

O15 – Automatic barrier on the grey-coloured semi-finished product conveyor belt (line 1) raised / lowered (Up: O15=1, Down: O15=0)

O16 – Automatic barrier 2 on the blue semi-finished product conveyor belt (line 2) raised / lowered (Up: O16=1, Down: O16=0)

O17 – Automatic barrier 3 on the blue semi-finished product conveyor belt (line 2) raised / lowered (Up: O17=1, Down: O17=0)

O18 – Assembly completed (false: O18=0, true: O18=1)

States systems are grouped according to subsystems as follows:

- Part receiving/processing/ejection subsystem
  - *S0 – Initial state, all devices are blocked waiting for the start button to be pressed, or the emergency stop button to be released*
  - *S1_1 – Waiting_for_the_raw_piece*
  - *S2_1 – Take_the_raw_part_from_the_CNC_input*
  - *S3_1 – Submit_raw_piece*
  - *S4_1 – Processing*
  - *S5_1 – Evacuation*
  - *S6_1 – CNC_Block1*

- *S7_1 – CNC_Block2*

➢ Raw material transport subsystem
  - *S1_2 – Idle*
  - *S2_2 – Active*

➢ Semi-finished and finished product transport subsystem
  - *S1_3 – Idle*
  - *S2_3 – Both lines active*
  - *S3_3 – Active_only_line1*
  - *S4_3 – Active_only_line2*

➢ Finished product assembly subsystem
  - *S1_4 – Idle*
  - *S2_4 – Active*
  - *S3_4 – Waiting_for_the_lid*
  - *S4_4 – Waiting_for_base*

Process state transition graphs based on inputs and outputs

State and transition graphs are important in PLC programming because they help to clearly design and understand how the automated system operates. The graphs divide the system operation into well-defined states and show the transition conditions between them, which makes the program logic easier to follow. By visually representing states and transitions, logical conflicts or unforeseen situations can be more easily observed before the program is implemented and allow for quick identification of the current state and the transition that is not working correctly.

Initially, I0=0, the system state is S0, waiting for the start button to be pressed. If the start button is pressed (I0=1), the subsystem states become S1_1, S2_2, S1_3 and S1_4, and the output O1 = 1 (the conveyors start).

If I2=1 (blue raw material detected), then a counter will be incremented, and the number of blue raw material objects will become 1. Output O2=1 (Pusher 1 blue material expands), the only state that changes are the state of the raw material transport subsystem, from S2_2 – Active to S1_2 – Idle. So, the next states are S1_1, S1_2, S1_3, S1_4. Analogous for I3=1, O3 becomes 1 and the state S2_2 – Active becomes S1_2 – Idle for the grey-coloured material.

If I4=1 (Presence sensor on the blue raw material conveyor belt is active), then O4 =0 (The automatic barrier on the blue raw material conveyor belt will lower) and the states remain unchanged. Similarly, I5=1, O5=0, the states remain unchanged.

If I6=1 (Raw material presence sensor at CNC1 input has detected an object), O6=1 (CNC1 robotic arm moves left 90o, takes the part), the state that changes is S1_1. The new state is S2_1, the transition being from Waiting_for_raw_part to Taking_raw_part_from_CNC_input. Analogous for I7=1, O7=1, S1_1 –> S2_1.

If I10=1 (CNC1 robotic arm stroke limit sensor detected that the arm is at 0o), then O8=1 (CNC1 robotic arm moved straight 90o to return to 0, depositing the part for processing) and the state transition is S2_1 – Take_raw_piece_from_CNC_input to S3_1 – Deposit_raw_piece. From this state, regardless of the other inputs, from S3_1 – Deposit_raw_piece the transition is made to S4_1 – Processing and then to S5_1 – Discharge.

Analogously for I11=1, then O9=1, the transition S2_1 –>S3_1 –>S4_1 –>S5_1.

After the part has been evacuated from CNC1 then I14 =1 (Blue semi-finished product presence sensor detects an object at the CNC1 output), O4 = 1 (Up, the barrier rises) and the S1_2 Idle state of the blue raw material transport system becomes S2_2 – Active. Analog, I15=1 Grey-coloured semi-finished product presence sensor detects an object at the CNC2 output), O5 = 1 (Up, the barrier rises) and the S1_2 Idle state of the grey-coloured raw material transport system becomes S2_2 – Active.

If I14=1, then a counter is incremented and the number of blue blanks becomes 1. When the counter reaches value 2, O14=0 (Automatic barrier 1 on the blue blank conveyor belt (line 2) is lowered) and CNC1 will stop.

The state of the processing subsystem becomes S6_1 – CNC_Block1 regardless of the state we are in, and the state of the semi-finished and finished product transport subsystem will change from S2_3 – Active_both_lines to S4_3 – Active_only_line2. From state S6_1, the previous state is returned when I18 =1 (Finished product presence sensor detected an object on the belt, decrementing the counter of blue semi-finished products), and from S3_3, the previous state is returned.

Analogously, I15=1, a counter will increment its value. When reaching the value 2, O15=0 (The automatic barrier on the grey-coloured semi-finished product conveyor belt (line 1) is lowered) and CNC2 will stop, the state becoming S7_1 – CNC2_Block. The state of the semi-finished product and finished product transport subsystem will change from S2_3 – Active_both_lines to S3_3 – Active_only_line1. From the S7_1 state, it returns to the previous state when I18=1, decrementing the number of grey-coloured semi-finished products. At the same time, the transition S3_3 to S2_3 is made.

If I19=1 (Blue base detection sensor on line 2 waiting for assembly is active) then the state changes from S1_4 – Idle to S3_4 – Waiting_for_lid and O17=0 (Automatic barrier 3 on the blue semi-finished product conveyor belt (line 2) is lowered.

If I21=1 (Grey-coloured lid detection sensor on line 1 waiting for assembly is active) then the state changes from S1_4 – Idle to S4_4 – Waiting_for_base and O17=0 (Automatic barrier 3 on the blue semi-finished product conveyor belt (line 2) is lowered.

If from state S3_4, I21 becomes 1, or from state S4_4, I19 becomes 1, it goes to state S2_4 – Active and O17=1 (Automatic barrier 3 on the blue semi-finished product conveyor belt (line 2) is raised. After the finished product passes barrier 3, I18=1 and output O18 = 1 (assembly was successfully completed). The signal from I18 is used to increment a counter that will help determine the total number of manufactured products.

Summarizing the above description, we have:

Initial state:

S0: Waits for the start button to be pressed (I0=0).

Main transitions:
S0 → S1_1, S2_2, S1_3, S1_4 (I0=1, O1=1)
Transits for blue raw material transport:
S2_2 → S1_2 (I2=1, O2=1)
S1_2 → S2_2 (I14=1, O4=1)
Transits for grey raw material transport:
S2_2 → S1_2 (I3=1, O3=1)
S1_2 → S2_2 (I15=1, O5=1)
Transitions for CNC1:
S1_1 → S2_1 (I6=1, O6=1)
S2_1 → S3_1 (I10=1, O8=1)
S3_1 → S4_1 (Automatic)
S4_1 → S5_1 (Automatic)
S5_1 → S1_1 (Automatic)
S1_1 → S6_1 (I14=2, O14=0)
S6_1 → S1_1 (I18=1,O14=1)
Transitions for CNC2:
S1_1 → S7_1 (I15=2, O15=0)
S7_1 → S1_1 (I18=1)
Assembly transitions:
S1_4 → S3_4 (I19=1, O17=0)
S1_4 → S4_4 (I21=1, O17=0)
S3_4 → S2_4 (I21=1, O17=1)
S4_4 → S2_4 (I19=1, O17=1)
S2_4 → S1_4 (I18=1, O18=1)
Transits for semi-finished goods transport:
S1_3 →S2_3 (Automatic)
S2_3 → S4_3 (I14=2, O14=0)
S4_3 → S2_3 (I18=1,O18=1)
S2_3 → S3_3 (I15=2, O15=0)
S3_3 → S2_3 (I18=1,O18=1).

For reasons related to the readability of the graphs, we chose to represent the states and their transitions on subsystems, starting each time from state S0 - the initial state.

Figures 6-9 present the state transition graphs for the part receiving/processing/ejection subsystem, the raw material transport subsystem, the semi-finished product transport subsystem, and the assembly subsystem.

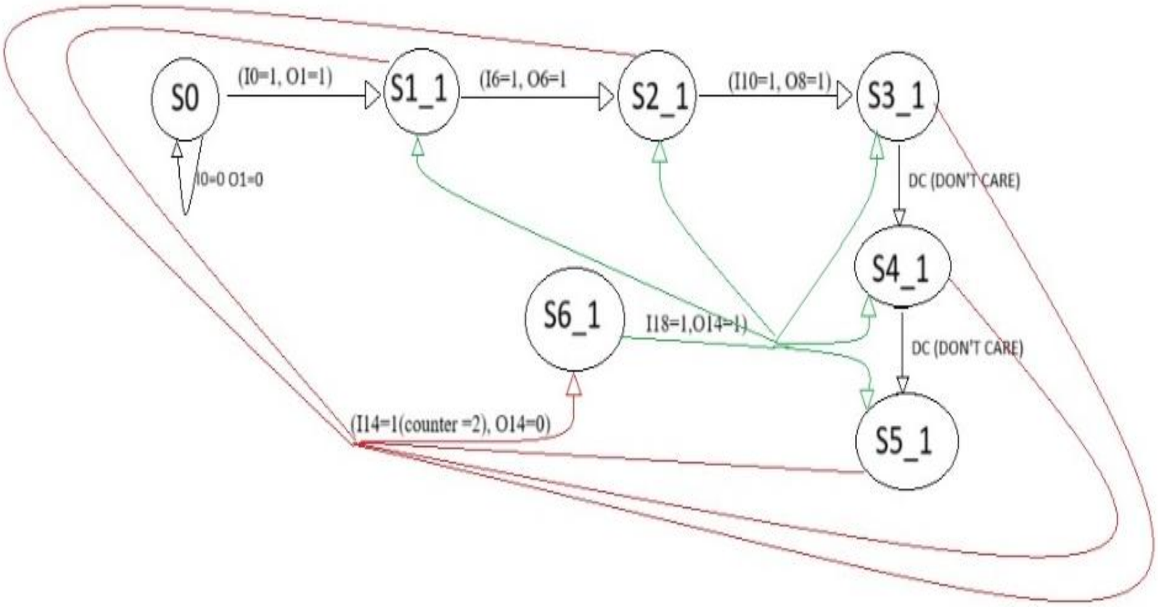


Figure 6. *State transition graph for the part pick-up/processing/eject subsystem*

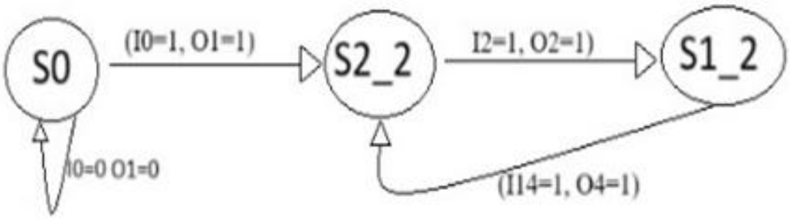


Figure 7. *State transition graph for the raw material transport subsystem*

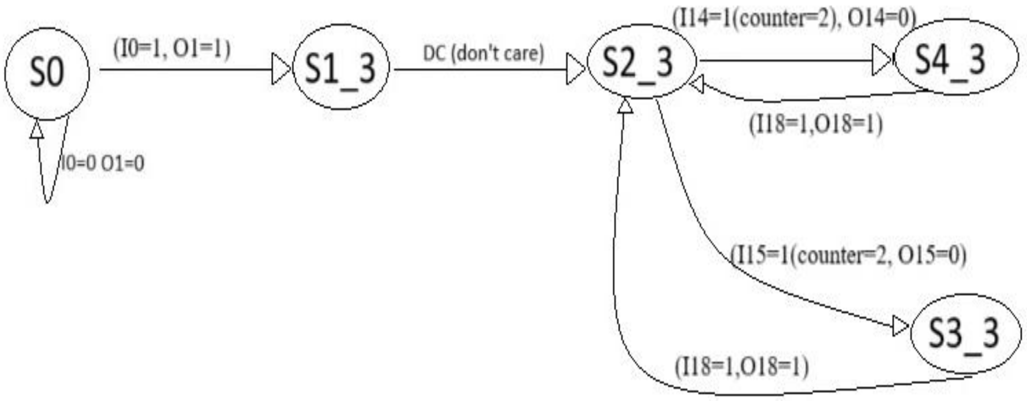


Figure 8. *State transition graph for the semi-finished product transport subsystem*

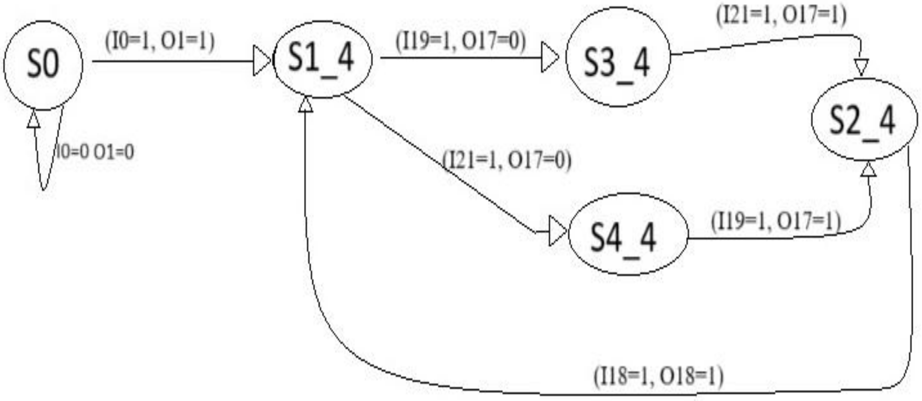


Figure 9. *State transition graph for the assembly subsystem*

FACTORY I/O AUTOMATIC IMPLEMENTATION

Factory I/O is a 3D factory simulator designed to facilitate the learning of automation technologies. This program allows users to create and simulate complex industrial scenarios, being mainly used for training in the field of PLC (Programmable Logic Controller).

With an intuitive and easy-to-use interface, Factory I/O includes an extensive library of industrial parts, allowing the construction of customized scenarios in two simulation ways: edit and run.

In edit mode, users can build and modify scenarios, and in run mode, they can test and simulate the created scenarios. The program also allows fault injection to test system reactions.

Factory I/O includes advanced 3D camera navigation and control options and supports multiple I/O (input-output) drivers. I/O drivers are essential for communicating with external controllers.

These drivers are integrated into the program and allow interaction with various automation technologies. Users can select a driver from the list and open the configuration panel to conFigure it accordingly.

Of interest for this work is the Control I/O driver. It is brand-independent and is designed specifically for Factory IO. With Control I/O, users can develop programs using functional block diagrams, using the most common functions available on real PLCs. Virtual commissioning of automation cells using functional blocks reflects current trends in Industry 4.0 education and practical deployment [29],[32]. Figure 10 shows the Control I/O driver interface.

The blocks available in Control I/O are of the type Inputs, Outputs, Memories (blocks that store state/value), Sources (sources, which can be numeric or Boolean) and Function Blocks (functional blocks that perform specific functions, combinational logic circuits, e.g. AND, OR gates, etc., sequential logic circuits, e.g. JK flip-flop circuit, etc.). Figure 11 shows the available blocks.

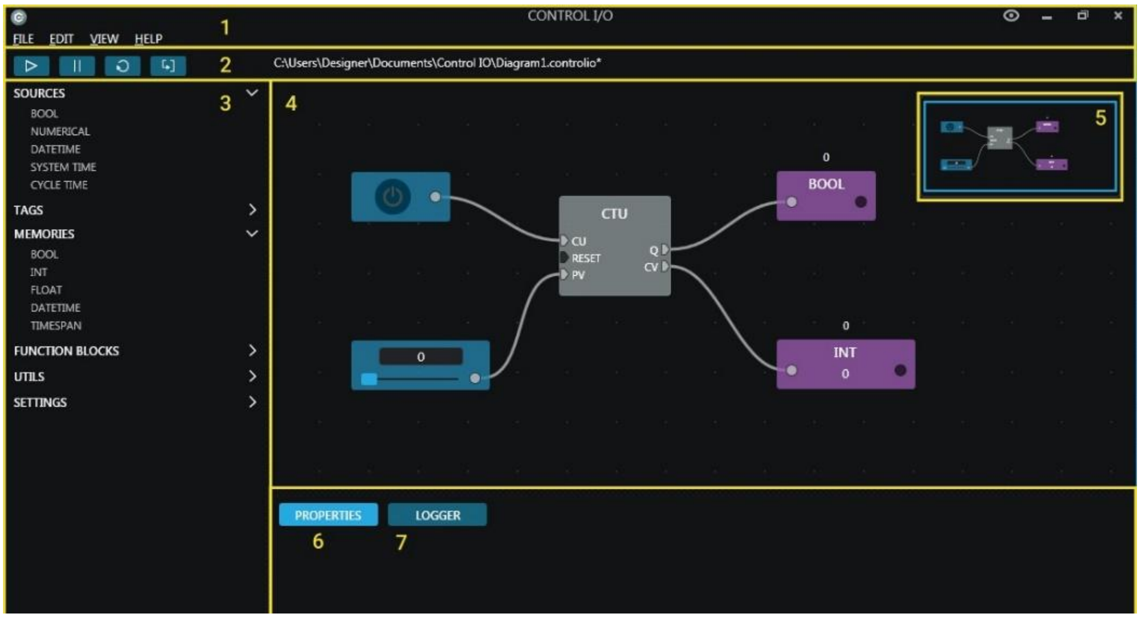


Figure 10. Control I/O driver interface (Factory I/O)

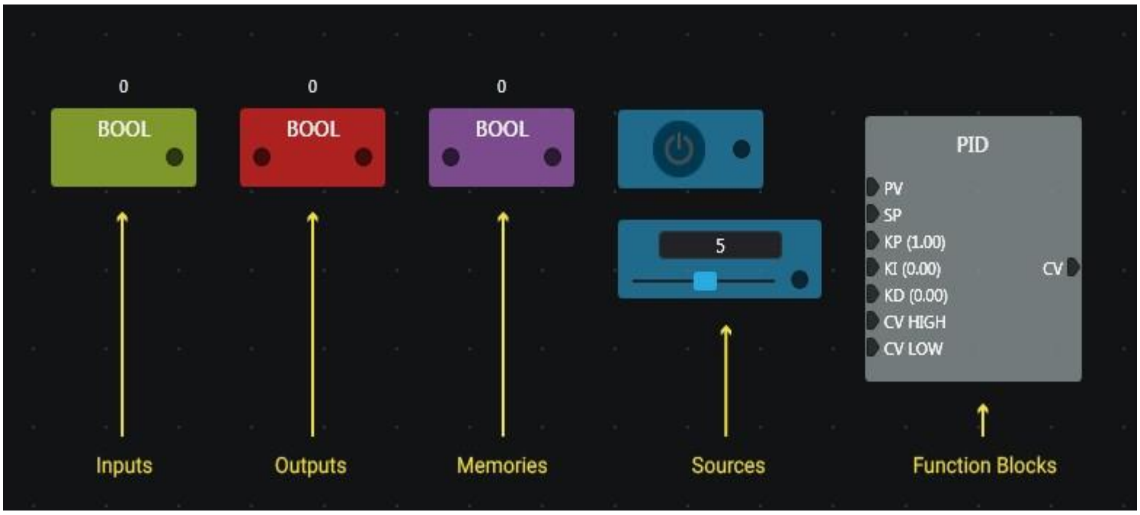


Figure 11. Block types available in I/O Control (Factory I/O)

Strictly referring to the practical application carried out in Factory I/O through which we simulated an automaton that controls a flexible manufacturing system with two processing machines, the Inputs, Outputs, Memories, Sources blocks were used, and from the set of functional blocks, the following: AND (And), OR (Or), Not (Negative), XOR (Exclusive Or), Counters (Counters), RS (Reset – Set, with priority for Reset), SR (Set-Reset, with priority for Set), JK (JK flip-flop circuit), Timers (TOF – deactivates an output after a preset time, TON – activates an output after a preset time). To describe the implementation method in I/O Control, we will address the process logic in several sections and subsystems.

Starting the system. If the Start button is pressed and the Emergency Stop button is not pressed, the conveyors start and the other elements in the process become active. If there is a situation where both buttons are pressed, then the Emergency Stop button has priority. This logic was implemented using the RS block and a screenshot of the application is shown in Figure 12.

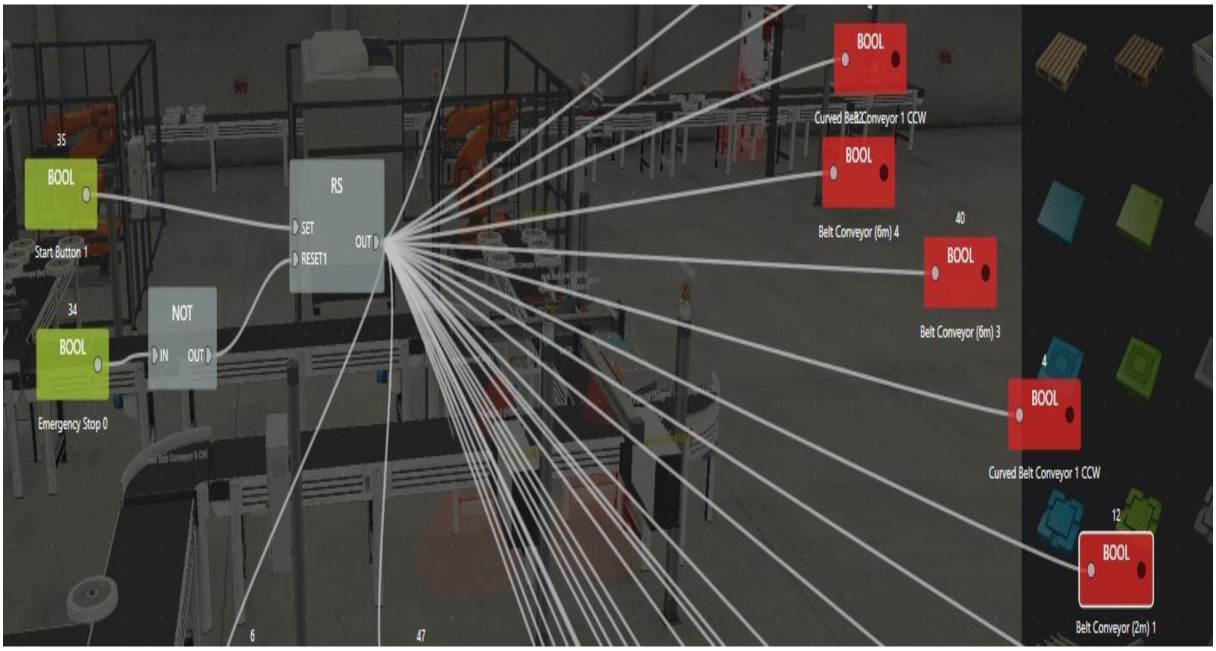


Figure 12. *System startup logic (Factory I/O)*

Raising / Lowering automatic barriers on conveyor belts is conditioned by certain signals received from various sensors. There are situations in which the programming has been done so that the barriers are activated when signals are received from the sensors without taking into account time conditions or the number of objects on the belt, these being implemented according to Figure 13, in which the barrier rises if the input at address 8 is active. The barrier lowers if the input at address 28 is active. If the two inputs are active simultaneously, input 8 will have priority, so the barrier will rise.

There are also situations in the application when it was necessary to consider the time elapsed since the appearance or disappearance of a condition, according to Figure 14. Applying the logic of the JK flip-flop, when activating the input at address 24, 600 ms will be waited, after which the J input will become 1. The K input will initially be set to 0 and after 800 ms it will be set to 1. Thus, the barrier will rise after 600 ms from the sensor activation, after 800 ms, the two inputs J and K both become 1 and the barrier lowers.

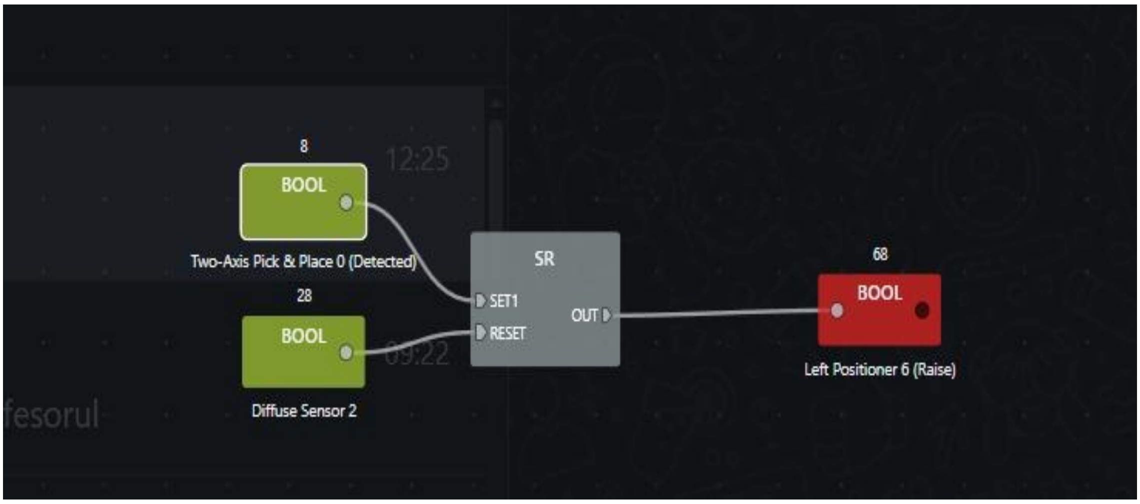


***Figure 13**. Barrier I raising / lowering conditions (Factory I/O)*

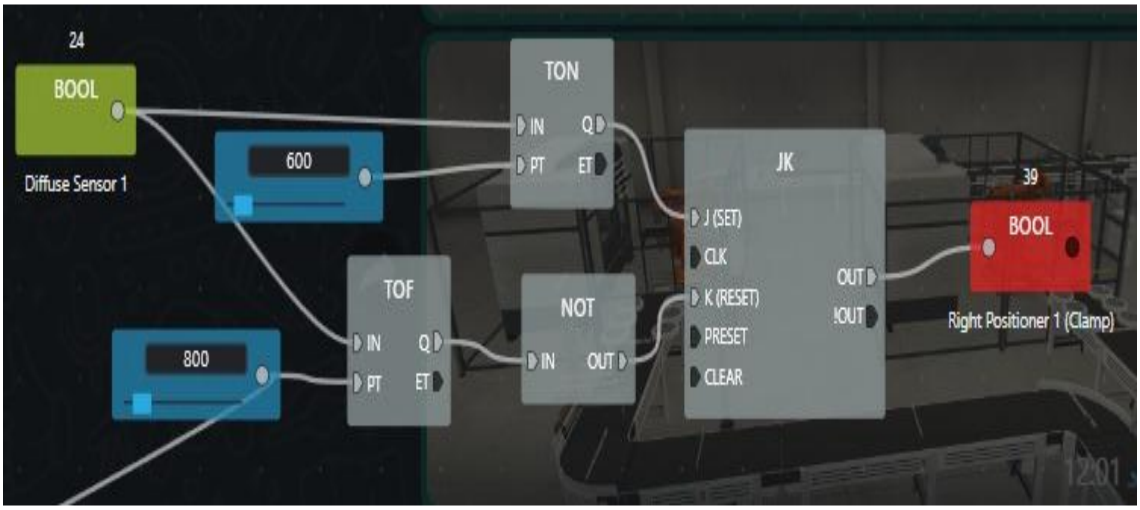


***Figure 14**. Barrier II raising / lowering conditions (Factory I/O)*

Counting objects on conveyor belts to activate/deactivate outputs is also conditioned by certain signals received from various sensors. For this purpose, we used counters that count up when a signal is activated, or count down when a signal is activated, or count both up and down, the signals being given by different sensors.

A representation of this implementation is in Figure 15. If input 32 becomes active, the counter will increment its value. If input at address 33 becomes active, the counter will decrement its value. The output of the counter QU becomes active when the current value is equal to the value at input PV (prescript value). The output at address 5 (the pusher) will be activated only if the value at address 42 and the value at address 2 are simultaneously 1. Otherwise, the pusher is not active.

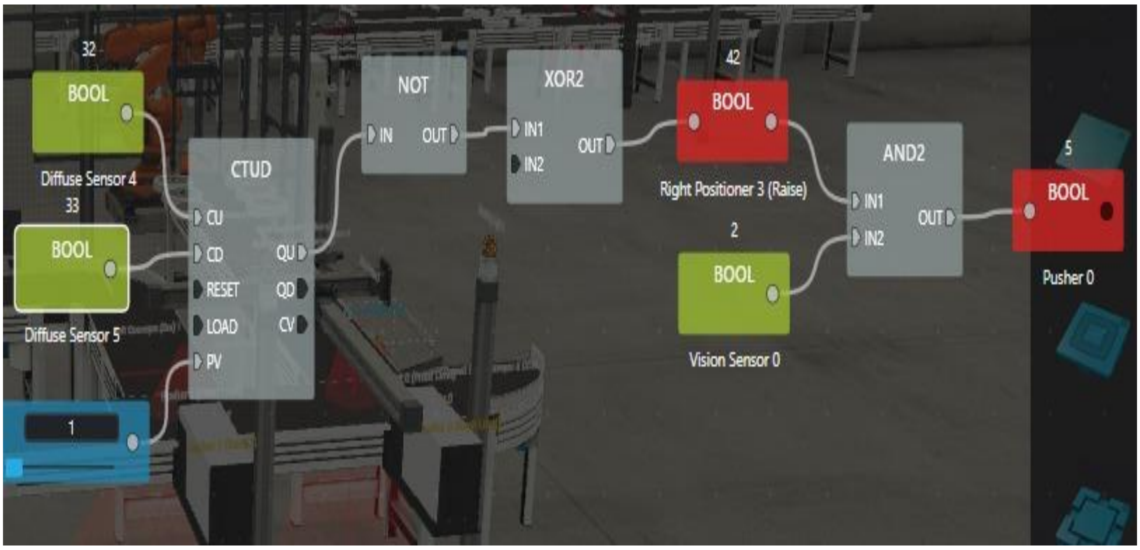
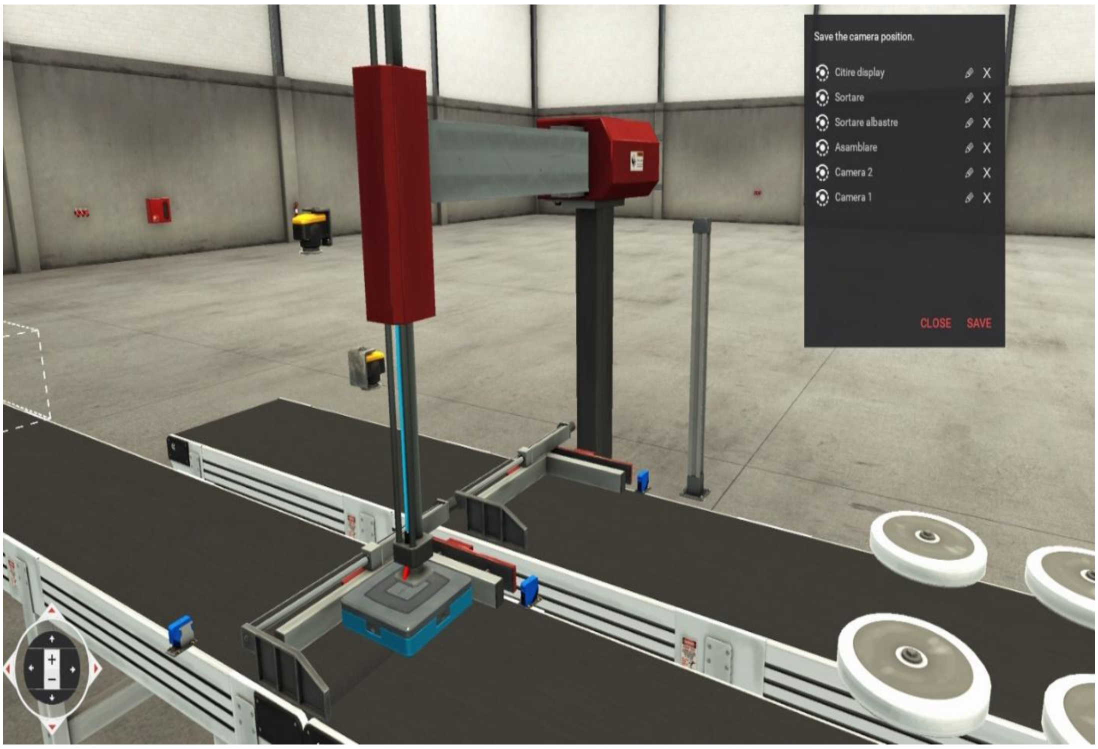


***Figure 15**. Conditions for activating/deactivating counter-conditioned outputs (Factory I/O)*

Figures 16-18 show screenshots from the application execution. Together, they provide a clear visualization of the PLC-based control logic in action, showing how the subsystems work together to ensure correct sequencing and stable operation of the cell. By observing the states of inputs, outputs, and intermediate control elements in these screenshots, it becomes easier to understand how the program monitors the process and responds dynamically to changes in system conditions.

Save the camera position.

***Figure 16**. Screenshot of the two processing machines working in parallel (Factory I/O)*



Save the camera position.

Figure 17. *Screenshot of the assembly machine and the two assembled parts (Factory I/O)*

Figure 18. *Screenshot of the assembly machine and*
the counter of correctly assembled parts (Factory I/O)

The transition from simulating a flexible manufacturing cell in Factory I/O to physical implementation is an essential step in validating and applying the automation solution in practice. In the simulation phase, the PLC program logic, sequence operation, and interaction between sensors and actuators are tested in a virtual environment, without risk to the equipment. After verifying the correctness of the program, it can be transferred and adapted for the real system, where physical equipment such as sensors, motors, and conveyors is connected. Adjustments related to response times, wiring, or real operating conditions may occur at this stage. Thus, simulation in Factory I/O reduces development time, minimizes errors, and facilitates the efficient implementation of the automated system in the real industrial environment.

CONCLUSIONS

In this work, a control system for a flexible manufacturing cell was designed and implemented, using a programmable logic controller and an industrial simulation environment. The proposed control system demonstrates operational stability and adaptability, supporting recent findings on digital twin and intelligent control applications in flexible manufacturing [31],[33]. By structuring the system into functional subsystems and clearly defining the inputs, outputs, and states, it was possible to model the process as a coherent and easily understandable finite state machine.

The simulation performed in Factory I/O allowed validation of the system's operating logic, highlighting its ability to manage parallel processing flows, prevent deadlocks, and ensure correct synchronization between the transport, processing, and assembly subsystems. The use of counters, timers, and memory elements contributed to obtaining a stable and predictable behaviour of the system. The results demonstrate that the proposed solution is functional and efficient for managing a flexible manufacturing system with two CNC machines. Additionally, the study emphasizes the advantages of using industrial simulators in the design and testing process, allowing for the early detection and correction of potential errors before physical implementation.

The originality of this study lies in the integration of formal finite state machine modelling with industrial simulation to create a digital twin of the flexible manufacturing cell, providing a framework for real-time monitoring, predictive analysis, and potential optimization of production flows. Unlike conventional PLC implementations that focus primarily on hardware configuration or isolated control tasks, the proposed approach ensures bidirectional logical coordination between transport, processing, and assembly subsystems, enhancing both process reliability and operational transparency.

A significant contribution consists in the development of a deadlock-prevention mechanism based on state-dependent logic and bidirectional counters, enabling automatic flow regulation and congestion avoidance. The synchronization strategy for asynchronous parallel processing and conditional assembly represents another innovative aspect, as system behaviour dynamically adapts to the order of semi-finished product arrival. Furthermore, the study demonstrates a coherent correspondence between theoretical state-based modelling and its practical realization using PLC functional blocks within an industrial simulation environment. The validation performed in Factory I/O confirms the stability, scalability, and practical applicability of the proposed control architecture, offering a replicable framework for advanced flexible manufacturing system design.

In the future, the presented system can be expanded by integrating additional functionalities, such as performance monitoring, cycle time optimization, or the implementation of intelligent control strategies, further contributing to the efficiency, flexibility, and digital transformation of modern industrial processes.

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