ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

INDUSTRIAL AUTOMATION, CS-487

Course Project

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Project description

This year project considers a paint production plant made of four mixing stations. As illustrated in Figure 1 below, each color mixing station is composed of 5 color tanks (cyan, magenta, yellow, black and white) and one mixing tank. Each color tank is controlled via an output valve, and the mixing tank can be emptied via a dedicated pump and output valve. Each tank has four sensors detecting the very low, low, high and very high levels of color as well as a flow meter and level sensor providing respectively the actual amount of paint leaving each tank and the remaining amount of paint left in a tank.

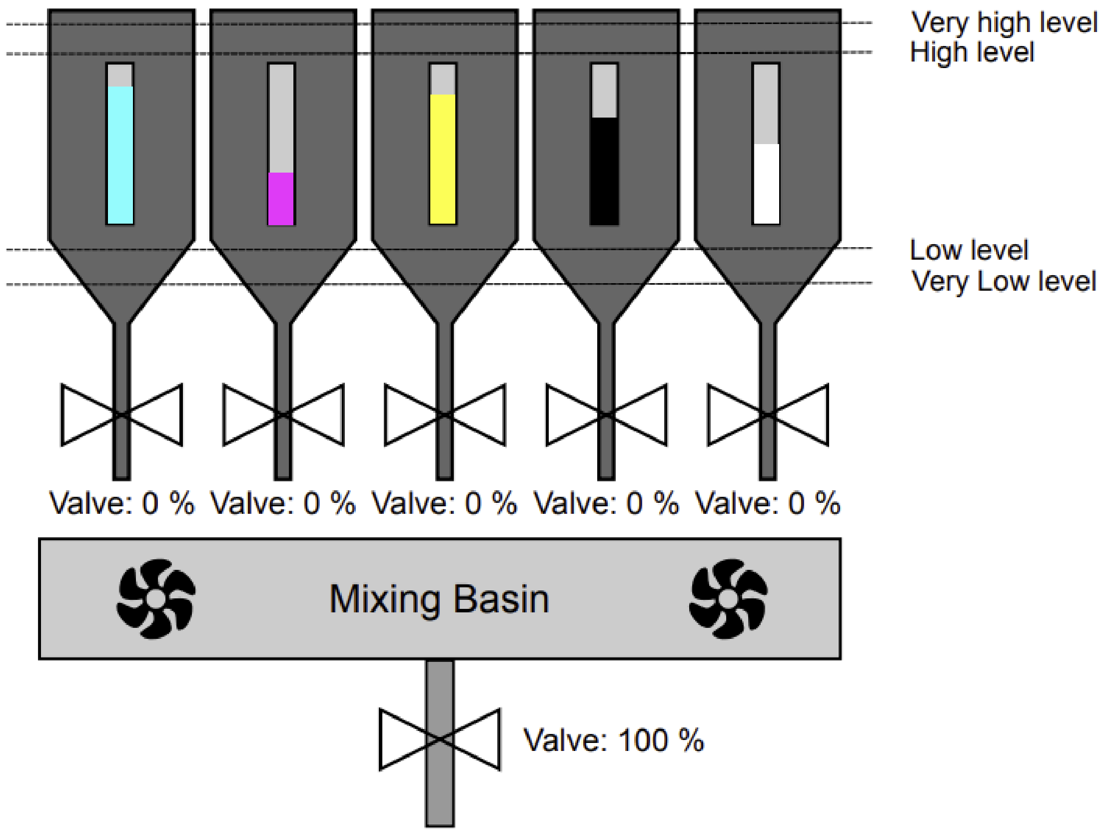

Figure 1: Schematic representation of one of the four color mixing stations

The goal of the project is to provide the monitoring and control infrastructure to operate such a plant by defining the automation architecture from the I/O cards to the SCADA system.

Work distribution

The various sub-tasks in the project are distributed among the group members according to the following table.

Table 1: Distribution of tasks among group members

Task	Group member
Report proofreading	All
Functional analysis (Part 1) & Introduction & Conclusion	Alexandre LECHARTIER
Automation architecture (Part 2)	Héctor M. RAMIREZ C.
Supervision (Part 3)	David KWAKYE Wilhelm WIDLUND MELLERGÅRD
Qualitative dependability analysis (Part 4)	Defne CULHA

1 Functional Analysis

The plant is composed of 4 mixing station. Thus, a mixing station is composed of 5 color tanks and a mixing tank. In the following is the lookup table for making correspond each color to a tank number used for convention:

Table 2: Table of used colors per tank number

Used color per tank number	
tank number	color in tank
tank 0	mixing
tank 1	cyan
tank 2	magenta
tank 3	yellow
tank 4	black
tank 5	white

For each mixing station, we use the same signals with the same naming convention, but we add the station number in front of the name. We define the high level signal of the mixing tank as being high_tank_0 for a mixing station. This means that for mixing station 1, we name the signal using this pattern X_high_tank_0, as 1_high_tank_0, where X is the mixing station number.
For mixing station 1, we will have 1_high_tank_0.
For mixing station 2, we will have 2_high_tank_0.
For mixing station 3, we will have 3_high_tank_0.
For mixing station 4, we will have 4_high_tank_0.
A full list of all the signals can be found in the Appendix section in tables 9, 10, 11 and 12.

Identify for the whole plant the following points:

- List of input signals (sensors) with their types and ranges

  Per tank, we need to be able to measure the level for this we use switch sensors (with floats) to measure discrete levels and time of flight sensors (with ultrasounds), to measure continuous levels. We also use electrical boards to measure the current drawn by the motors of the mixers. And a camera to measure the color in the tank. We also assume that the station is behind a fence and that when the operator enters the station, operation is resumed. This is to avoid any injury of the operator. Additionally, we only have a sensor for the level very high of the mixing tank, as we will need it to be sure of when the tank overflows.

Table 3: Table of input signals (sensors) with their types and ranges

List of input signals (sensors) with their types and ranges			
input signal	type	range	naming convention
tank very low level tank 1	discrete	0 or 1	very_low_tank_1
tank very low level tank 2	discrete	0 or 1	very_low_tank_2
tank very low level tank 3	discrete	0 or 1	very_low_tank_3
tank very low level tank 4	discrete	0 or 1	very_low_tank_4
tank very low level tank 5	discrete	0 or 1	very_low_tank_5
tank low level tank 1	discrete	0 or 1	low_tank_1
tank low level tank 2	discrete	0 or 1	low_tank_2
tank low level tank 3	discrete	0 or 1	low_tank_3
tank low level tank 4	discrete	0 or 1	low_tank_4
tank low level tank 5	discrete	0 or 1	low_tank_5
tank high level tank 1	discrete	0 or 1	high_tank_1
tank high level tank 2	discrete	0 or 1	high_tank_2
tank high level tank 3	discrete	0 or 1	high_tank_3
tank high level tank 4	discrete	0 or 1	high_tank_4
tank high level tank 5	discrete	0 or 1	high_tank_5
tank very high level tank 0	discrete	0 or 1	very_high_tank_0
tank very high level tank 1	discrete	0 or 1	very_high_tank_1
tank very high level tank 2	discrete	0 or 1	very_high_tank_2
tank very high level tank 3	discrete	0 or 1	very_high_tank_3
tank very high level tank 4	discrete	0 or 1	very_high_tank_4
tank very high level tank 5	discrete	0 or 1	very_high_tank_5
outflow tank 0	continuous	-100 to $100m^2/s$	outflow_tank_0
outflow tank 1	continuous	-100 to $100m^2/s$	outflow_tank_1
outflow tank 2	continuous	-100 to $100m^2/s$	outflow_tank_2
outflow tank 3	continuous	-100 to $100m^2/s$	outflow_tank_3
outflow tank 4	continuous	-100 to $100m^2/s$	outflow_tank_4
outflow tank 5	continuous	-100 to $100m^2/s$	outflow_tank_5
level tank 0	continuous	0 to 100%	level_tank_0
level tank 1	continuous	0 to 100%	level_tank_1
level tank 2	continuous	0 to 100%	level_tank_2
level tank 3	continuous	0 to 100%	level_tank_3
level tank 4	continuous	0 to 100%	level_tank_4
level tank 5	continuous	0 to 100%	level_tank_5
current drawn by mixer's motor 1	discrete	0 to 100%	mixer_current_1
current drawn by mixer's motor 2	discrete	0 to 100%	mixer_current_2
door open	discrete	0 or 1	door_open

- List of output signals (actuators) with their types and ranges

  To be able to mix paint accurately, we need to be able to precisely control the output valves. When the new color is mixed, we may want to output all the paint as fast as possible. In this case, we use the pump with the fully opened valve.
  Also, depending on the process and the type of paint, we may want to modulate the mixing speed for better efficiency or faster production.

Table 4: Table of output signals (actuators) with their types and ranges

List of output signals (actuators) with their types and ranges			
output signal	type	range	naming convention
output valve tank 0	continuous	0 to 100%	output_valve_0
output valve tank 1	continuous	0 to 100%	output_valve_1
output valve tank 2	continuous	0 to 100%	output_valve_2
output valve tank 3	continuous	0 to 100%	output_valve_3
output valve tank 4	continuous	0 to 100%	output_valve_4
output valve tank 5	continuous	0 to 100%	output_valve_5
emptying pump tank 0	discrete	0 to 100%	empyting_pump_0
mixing basin mixer speed	continuous	0 to 100%	tank_speed_0

- List of alarms to be displayed to the plant operators

Table 5: Table of alarms to be displayed to the plant operators

List of alarms to be displayed to the plant operators		
alarm	description	naming convention
very low tank 1 very low tank 2 very low tank 3 very low tank 4 very low tank 5	triggered when the tank level is under very low level marker	very_low_1 very_low_2 very_low_3 very_low_4 very_low_5
low tank 1 low tank 2 low tank 3 low tank 4 low tank 5	triggered when the tank level is under low level marker	low_1 low_2 low_3 low_4 low_5
very high tank 0	triggered when the tank level is over the very high marker	very_high_0
empty tank 0 empty tank 1 empty tank 2 empty tank 3 empty tank 4 empty tank 5	triggered when the tank is empty (use low level & tank level sensors)	empty_0 empty_1 empty_2 empty_3 empty_4 empty_5
emptying process tank 0 tank 1 tank 2 tank 3 tank 4 tank 5	triggered when the tank is being emptied (use valve command)	 emptying_process_0 emptying_process_1 emptying_process_2 emptying_process_3 emptying_process_4 emptying_process_5
leak of tank 0 leak of tank 1 leak of tank 2 leak of tank 3 leak of tank 4 leak of tank 5	triggered when valve closed & level sensor measures level decreases over some time $24 \gtrapprox \Delta t \gtrapprox 1$ *hour* (use tank level sensor over time & valve command)	leak_0 leak_1 leak_2 leak_3 leak_4 leak_5

uncontrolled level stagnation of tank 0 tank 1 tank 2 tank 3 tank 4 tank 5	triggered when valve command open & level not changing (use tank level sensor & valve command)	 level_stagnation_out_0 level_stagnation_out_1 level_stagnation_out_2 level_stagnation_out_3 level_stagnation_out_4 level_stagnation_out_5
uncontrolled input level stagnation of tank 0 from tank 1 from tank 2 from tank 3 from tank 4 from tank 5	triggered when tank 0 level rises & tank 1, 2, 3, 4 or 5 is leaking	 level_stagnation_in_01 level_stagnation_in_02 level_stagnation_in_03 level_stagnation_in_04 level_stagnation_in_05
measured level conflict of tank 0 of tank 1 of tank 2 of tank 3 of tank 4 of tank 5	triggered when tank's measured levels are in conflict (obtained from range sensors & level sensors)	 level_conflict_0 level_conflict_1 level_conflict_2 level_conflict_3 level_conflict_4 level_conflict_5

Alarms need to be displayed to the operators, to indicate critical possible situations that may lead to a system failure. For this, we use alarms on low levels of color tanks, to inform that a refill may be needed soon, and a very high level for the mixing tank to inform that the tank may overflow.
If one of the color tanks is empty, we trigger an alarm. If the mixing tank is empty when emptying it, we also trigger an alarm. An alarm is triggered when we empty any tank.
We also measure the level when the tank is not used, if its measured value decreases over time while its valve is closed, we trigger an alarm. If we want to output the content of any tank, and it doesn't work, we trigger an alarm. This may happen if the valve is open, but the level does not decrease. A similar alarm is triggered if we want to output paint from one color tank, but mixing tank level is not changing, e.g. for an open valve of a color tank and no change measured on the range sensor.
Another alarm is triggered if the measured levels on the tanks do not overlap, e.g. we measure a very high level on tank 1, but the range sensor says it's full at 50% only.

- List of interlocks and their logic

  We want to ensure that no liquid is coming in the mixing tank while we empty the mixing tank, so we close the color tank's output valves.
  If we measure an overfull of the mixing tank, we will raise the alarm and stop the process.
  When we input color in the mixing tank, we want to ensure that the mixing tank output valve is closed.
  We assume that the mixing fence is secured by a fence to avoid operators to go in and injure themselves. When an operator is in it, a special protocol has to be followed to avoid injuries. For example, operators have to go on the plant by groups of two. When the door is opened, the process is stopped. To turn it back on, we need to close the door and press on a button outside the fence area.
  In case of a too high leakage of any tank, the plant is shut down.
  When operating motors of the mixing palms, some unexpected incident may happen, such as having a palm stuck. This will lead to a motor in stalling state and may heat up the plant. To avoid any risk of fire, the current of the motor is measured. If the current is too high, the motor is stuck and the plant is shut down and needs emergency maintenance.

Table 6: Table of interlocks and their logic

List of interlocks and their logic		
Interlock	logic	naming convention
emptying tank 0	when the tank 0 is being emptied, close the tanks' 1, 2, 3, 4 & 5 valves	emptying_tank_0
max level tank 0	close tanks 1, 2, 3, 4 & 5 output valves, if tank 0 very high level is active and tank 0 level at 100%	max_level_tank_0
secure tank 0 operation	close tank 0 output valve, when output valves of tanks 1, 2, 3, 4 & 5	secure_operation_0
open fence operation	stop process when fence is open, until fence closed and start button is pressed	open_fence_process_stop
high leakage shut down	stop process, when tank output valve closed & big level decrease measured	high_leakage_process_stop
motor stall	stop process, when motor is stalling (motor uses too much current)	motor_stall_process_stop

2 Automation Architecture

2.1 Hardware description

2.1.1 Assumptions

About e**xplosive atmospheres**: The assignment document does not specify whether the paint is oil-based or water-based, hence our assumption was that the paint is water based. Explosive hazard is not considered, this way we avoided dealing with explosive atmosphere, otherwise we would have to use specialized equipment for this application, based in an additional hazard analysis for this type of zones which is not covered in the course.

Although some elements have an ATEX II 2G as a minimum, the **PLC has not special inputs and intrinsic-safe barriers were not considered**.

Pipe dimensions: 1" tubes in each tank. **Tank dimensions**: 2 meters long max, no specification about width. The tanks are considered to be stainless steel.
Filling of mixing tank by flow control with proportional valves.
No clean design directives as is not a food or pharmaceutical application and no safety PLC included.

The following elements are considered per subsystem. The final quantities are shown in Table 7.

2.1.2 Sensors (Inputs)

Figure 2: Point level sensor

Discrete point-level sensors: For this task, all sensors were considered to be the same type of sensor. All of them are **capacitive sensors**, that can be attached to the tanks with a special mounting. We were careful to verify that they could be used with liquid media. In this case the sensors work either with water-based liquids or oil-based liquids.
Number of pieces: 24
Name: LMC410, LMGCE-C12E-QSKG-1/US
Provider: IFM
Output: Discrete, PNP at 24V Connection: M12
Type of Mounting: G12 thread
Datasheet: LMC410 - Sensor for point level detection


Figure 3: Pressure level sensor

Continuous Level sensors: In this case a hydrostatic pressure sensor was selected for the level. This would avoid some complications compared to other sensors, because we have not a specific assumption about the dimensions of the tank, a pressure sensor would be practical for measuring the level of each tank by using the **hydrostatic pressure.**
Number of pieces: 6
Name: PS307A
Provider: IFM
Output: Continuos, 4 . . . 20 [mA] Connection: Has cable
Type of Mounting: Suspended in fluid.
Datasheet: PS307A - Hydrostatic submersible pressure transmitter


Figure 4: Flow sensor

Continuous Flow sensors: The chosen principle of this sensor is the **calorimetry**. This is particularly useful and practical for this application, as it does not need a big mounting space and can work either with oil or water-based liquids. It allows us to not worry much about the specific conductivity, density, or viscosity of the paint.
Number of pieces: 6
Name: SA2000 SAR12XDBFRKG/US-100 Provider: IFM
Output: Continuous, 4 . . . 20 [mA]
Connection: M12
Type of Mounting: G12 thread
Data sheet: SA2000 - Flow sensor


Figure 5: Interlock magnetic switch

Machine guarding door switch: This is a magnetic switch sensor, this is used for security reasons as the **door sensor**, the working station of the tanks is going to be closed with a security guard for safety reasons, thus we considered some magnetic switches to be sure that the gates are closed, this is going to be integrated to the PLC that we are currently using, no additional safety PLC's are considered.
Number of pieces: 1 pair
Name:RS2R
Provider: Eaton
Output: Discrete, 24V for a logic 1
Connection: M12
Type of Mounting: Contact less at gates, one in the frame, other in the the door to make sre is closed.
Data sheet: Interlock Sensor EATON RS2R

2.1.3 Actuators (Outputs)

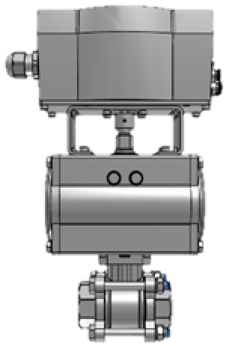

Figure 6: KVZB, actuator with controller

Ball valve with controller: For the actuator, a ball valve was chosen, as it allows to do flow control for liquid media. Although for flow control applications a butterfly valve is usually better, for small pipe diameters a ball valve is suitable. The whole actuator is provided as a single system with the vendor "FESTO". It was configured according to the application parameters discussed in the functional analysis.
The controller is a **CMSX** positioner from FESTO that has an embedded board that does the PID control. It is attached to the valve. It is actuated with pneumatic energy. The input is a 4-20 mA value from the PLC and the output is the position according to the input current.
The actuator has two parts, a 1" stainless steel ball valve, attached to a pneumatic actuator, that operates at 6 bar of air pressure. It is connected to the controller with a bridge. The details can be seen in the list attached to the datasheet.
Number of pieces: 6
Name: KVZB, C2653937
Provider: FESTO
Input: Continuous, 4 . . . 20 [mA] Output: ¼ spin according to input.
Pneumatic connection: 6mm tubing.
Electric connection: Cooper cable
Type of Mounting: G1 thread
Data sheets: Assembly KVZB

Figure 7: DM06 dedicated pump

Pump to empty mixing Basin. This is a pump is designed for chemical, water and paint applications, the size of the motor and the capacity is thought to be enough just for emptying the tank when remaining paint to change color needs to be flushed. The pump power, thus it's flow can be controlled with a frequency variator. The mixing basin matches the Tank 0 label.
Number of pieces: 1
Name: DM06P-SD3NU071M
Provider: DEBEM
Input power: 0.37 kW - 3phase voltage
Max flow rate: 7 m3/h
Suction connections: DN 25
Delivery connections: DN 20
Data sheet: DM06P

Figure 8: DM06 dedicated pump

Propeller for mixing Basin. The Mixer is an ADMIX RotoMAX II, which is a 5.5kW motor attached to a gearbox and a shaft with 3 blades. The motor is a Triphasic motor which will be regulated with a frequency variator to start and control speed of the blades. This is an assembled solution ready to install that can be mounted to the tank with an ANSI flange. For this project, as it is not specified the capacity of the mixing Basin and the amount of paint or the mixing process objective time, and since the propeller has 3 blades to mix, only one device is considered for the system, as we considered sufficient with the information about the process.
Number of pieces: 1 per tank
Name: Rotomax II 420 RMAX
Provider: ADMIX
Input: Power range 0.75kW - 5.5kW -3phase voltage
Output: Power at proportional frequency for speed control.
Electric connection: Cooper cable.
Mounting: Flange with 152 - 150 ANSI.
Data sheet:RotoMAX II

2.1.4 Control architecture

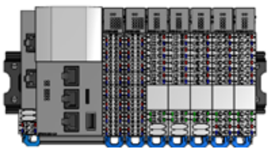

Figure 9: PLC: CPX-E

PLC: Communication protocol is not specified; therefore, the PLC was chosen to be flexible. The selected configuration of the PLC is Profi-Net which is the Siemens standard, nevertheless if there is the need to change to any other protocol this PLC can be configured with Ethernet IP, Ethercat or Modbus TCP, moreover it can also send data through OPC-UA, which will enable us to implement a SCADA system.

Number of pieces: 1
Name: CPXE
Provider: FESTO
Digital inputs: 2 modules with 16 DI
Analog Inputs: 3 modules with 4 AI
Analog Outputs: 2 modules with 4 AI
Protocol as slave: Profi Net
Protocol for SCADA: OPC-UA
Type of Mounting: DIN Rail for cabinet
Data sheet: CPX-E
Modules and configuration: 60E-CPN-2M3NI2NO - CPX-E parts

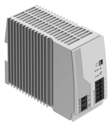

Figure 10: PLC: Power Supply CACN

Control power supply is dedicated to power the sensors, and control devices. Has enough Output current for the applications considered.
Number of pieces: 1
Name: CACN-3A-1-20-G2
Provider: FESTO
Input: 220V
Output: 24V - max 20 A
Datasheet: Power supply unit CACN

Figure 11: Frequency variator from ABB.ACS310

AC Motor Control: Frequency variator from ABB. It enables to start the mixer's and pump motors in a safe way, it also allows to regulate the speed if necessary to consume less power and save energy if the mixing doesn't need much power. As the motor is triphasic, so is the frequency variator, which was dimensioned based on the characteristics of the mixer's motor. It is also possible to use it for the pump to regulate it's speed and power, this way this same device is standardized for both applications.
Number of pieces: 2

Name: ACS310
For emprying pump: ACS310-03U-02A6-2
For mixing propeller: ACS310-03U-05A2-2
Provider: ABB
Input power: 3/60/220V
Input control: 4 - 20 [mA] (other options are available, but for our application this is the one to be used).
Output: 3/0-500/0-Vin
Datasheet: ABB ACS310

Figure 12: Sensor cable

Cables for machine guard switches, flow and point level sensors.
Number of pieces: 30
Name: EVC006 Vendor: IFM
Length: 10m
Connection: M12 socket and 4-wire end for PLC
Datasheet: EVC006 cable with socket

2.1.5 Control Architecture diagram

This is the architecture for a single tank and the mixing tank. The other 4 colour tanks have the same architecture but are omitted to simplify the diagram. It is important, however to remark that PLC can be used both as a OPC-UA server or client. In this case it will be used as a server, this will be more detailed in the Hardware to run SCADA system subsection.

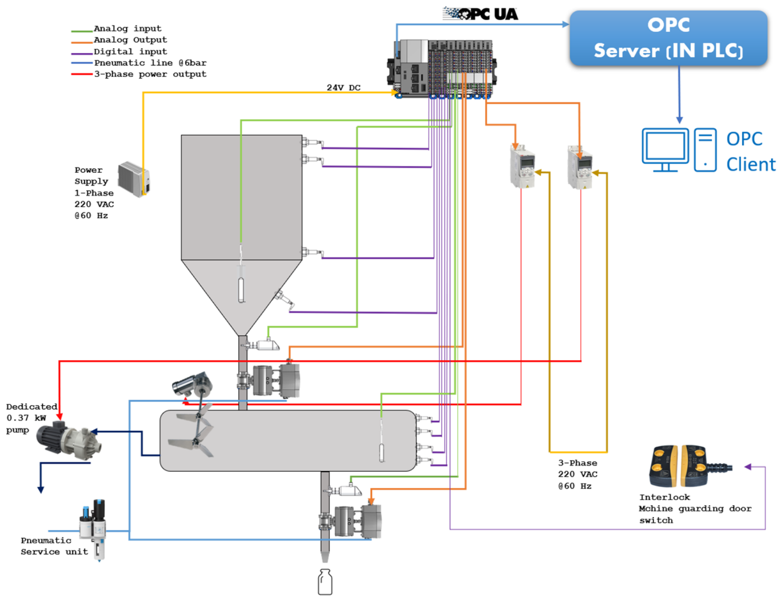

Figure 13: Layout of the plant susbsystems for a single tank and mixing magazin

About Outputs and outputs in the diagram

1. **Analog Inputs:** All analog inputs are 4-20 mA.
2. **Analog Outputs:** The analog outputs are also 4-20 mA.
3. **Digital inputs:** All of them are PNP senors, this means that the sensors will output 24V when the level is reached, and 0V otherwise. This is equivalent to have 24V as a logic 1 and 0V as a logic 0 in binary for the PLC.

Now that the subsystems of a single tank and the mixing tank are detailed, we are also showing the general layout of the solution with all the color tanks for a single subsystem. Some lines were reduced to 1 single line. However, this doesn't mean that they are a single cable, but they follow the connections showed in the single tank diagram: Fig.13

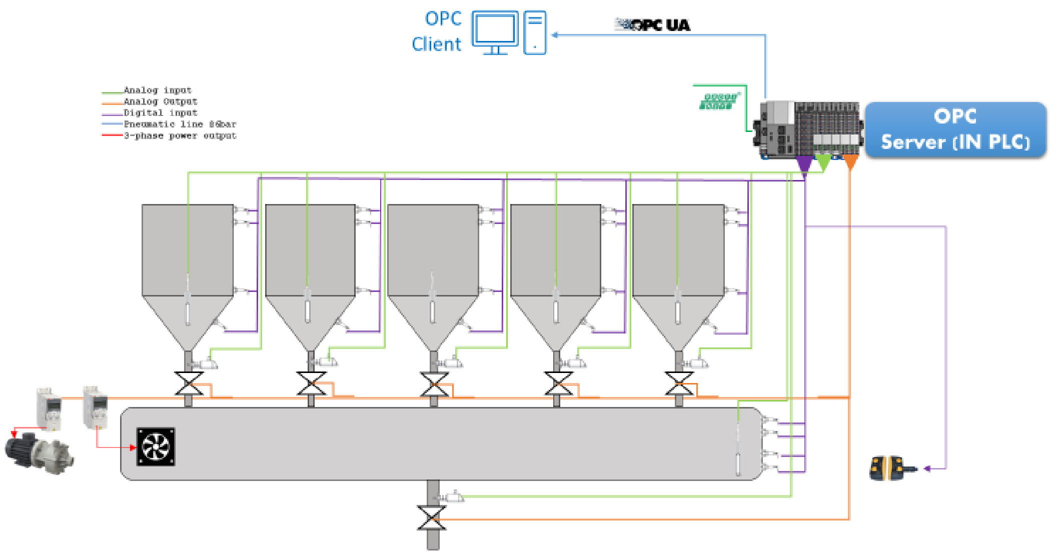

Figure 14: Layout of the plant in general

The complete list of elements in the plant can be seen in the table 7, this is only a summary of the total number of components used in the solution, the specific information of each one of them can be seen at the beginning of the section.

Table 7: List of all components in solution

Application	Class	Total Qty	Tech	Model
Level	Sensor	96	PNP	LMC410
Level	Cables	124	PNP	EVC006
Level	Sensor	24	4...20	PS307A
Dosage	Sensor	24	4...20	LMC410
Control	Control	4	PLC	60E-CPN-2M3NI2NO
Control	Control	4	Power source	CACN-3A-1-20-G2
Dosage	Actuator	24	4...20	KVZB C2653937
Dosage	Actuator	800	6 bar	PUN-H-6X1-BL
Dosage	Actuator	4	Service unit	MSB6-1/2:C3:J1-WP
Emptying pump	Control	4	Frequency variator	ACS310-03U-02A6-2
Mixing	Control	4	Frequency variator	ACS310-03U-05A2-2
Mixing	Control	4	Propeller	Rotomax II 420 RMAX
Emptying pump	Control	4	Centrifugal pump	DM06P-SD3NU071M
Machine guard	Safety	4	Door switch	RS2R

2.2 Hardware to run SCADA system

The selection of the PLC allows us to reduce the amount of hardware used, as the PLC CPX-E can be used both as an OPC server and/or OPC client. This way, the PLC will send the information required to the client, which in this case it will be a computer with a monitor, either in the monitoring room or in the operation area (plant level), as seen in Figure15

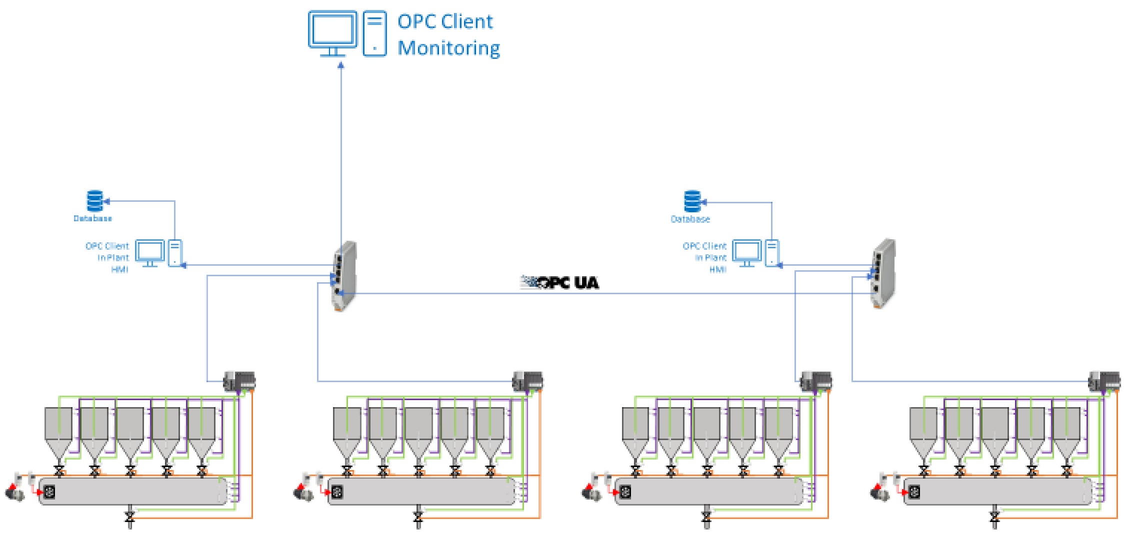

Figure 15: Layout of the SCADA system

The requirements for a computer were searched accordingly to the dimentions of the system, in this case the system is monitoring 4 PLCs, this system has less tha 1,000 sensors and tags to monitor, therefore we chose for a system with 64-bit Windows 11 OS, and more than 2 GHz with a dual-core processor, 40 GB of drive space (although expanded with HDDs) 4 GB RAM and a minimum of 100 Mb/s Ethernet or higher.
With the last considerations, in order to run the Scada system as shown, the devices needed are:

- 4 PLC - CPX-E with OPC Server/ Client included
- 2 Ethernet switch to connect the different clients with the server (or servers), in this case the device in the diagram is a Phoenix Contact 1005N with 5 ethernet ports.
- 1 computer as main server/client of the SCADA system in the monitoring room and 2 as clients to use in plant as HMI, this will allow to change parameters locally and see the status of 2 systems in plant individually. The CPUs were selected based on the mentioned requirements in this section. Phoenix contact BL RACKMOUNT 4U meets these requirements for industrial computers, which has:
  - Processor: Intel® Core™ i3-9100TE 2.2 GHz.
  - OS: Windows® 10 IoT Enterprise.
  - RAM: 8 GB DDR4 SODIMM.
  - Storage: 8 GB DDR4 SODIMM.
  - Network: 2x Ethernet (10/100/1000 Mbps), RJ45.
  - Monitor: 22 inch Semi industrial Monitor for the control room to visualize the process. Monitor from AG NEOVO
- 2 Storage unit for data base. In this case is a HDD connected to the clients in the plant, which will store the processed data. The data will be distributed in the two storage units for better availability in case that historical data is needed for optimization.

  Note: The computers will be using tango as software for the SCADA system.

The Computer in the plant will do the management of alarms, storage and visualization of the system. For the software part we will be using Tango.

3 Supervision

3.1 Synoptic views

3.1.1 Planned synoptic views

For our synoptic view, we chose to use a hierarchy with 3 stages. The first stage is the Process Area Overview. It displays the general state of the 4 mixing station. In these windows (drawn in figure 16) we have all the information to assess the current status of each mixing station. We know what the process is supposed to be, and we have a clear view of events and notifications. We chose to use color to help the viewer to see in one blink if something is wrong and require immediate attention, in addition to displaying the events in order of severity. Once problems are noticed, the supervisor can click on the `Detailed view` button to get to the second level of the hierarchy, for each mixing station respectively.

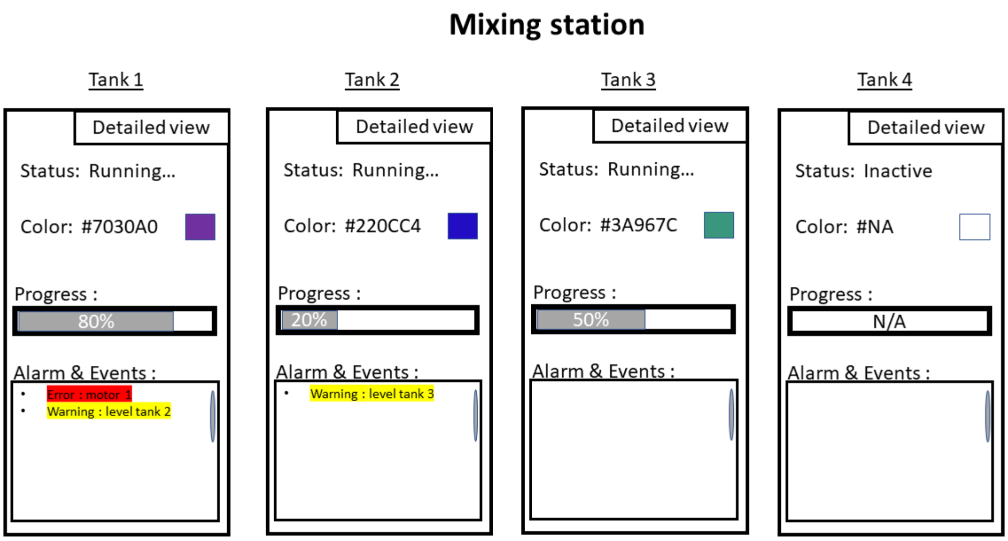

Figure 16: Process Area overview

The second Level is the Process Unit Control page (figure 17). This one contains information regarding each tank in a specific mixing station. The user can understand what could be happening with the current values of sensors on display. This layout allows anyone to see if the level of paint is still acceptable or if a pump doesn't function as expected. If time dependent information is needed, we can navigate to the third layer, with the `Detailed view` button.

The third layer (figure 18) contain graphs which show the evolution of values from the chosen tank over time. It could be useful if we need the history to know how quickly things have changed.

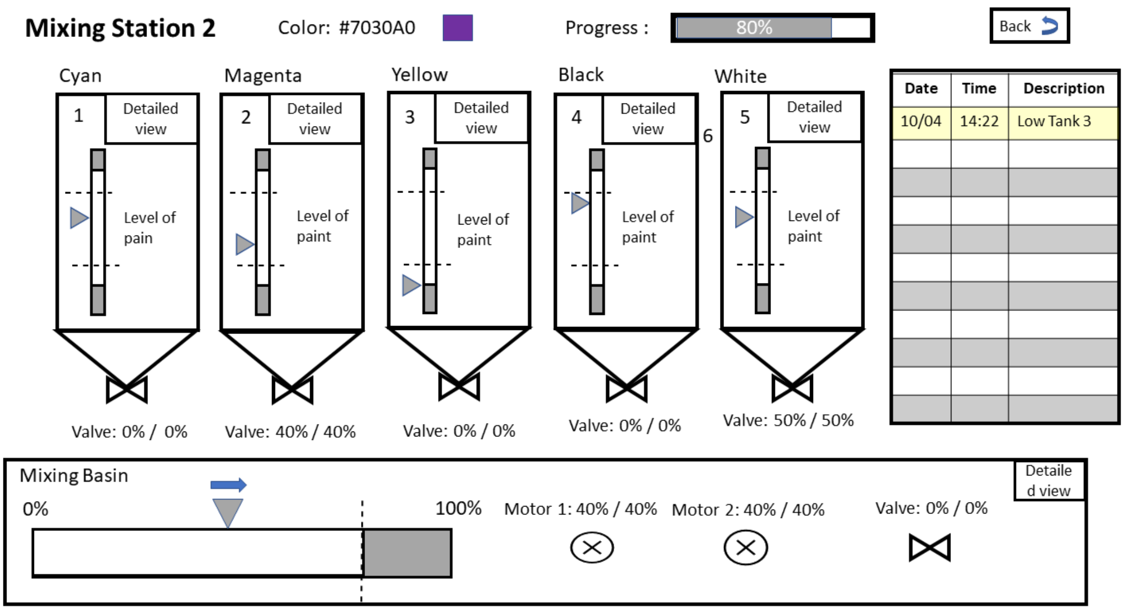

Figure 17: Proposed Process Unit Control

Figure 18: Proposed Process Unit Detail

3.1.2 Implemented synoptic views

To implement a part of the synoptic view framework proposed above, we used the Python code skeleton provided for the project. We have implemented a Process Unit Control view, and a Process Unit Detail view, in the given GUI. We have also augmented the given plant simulator with a framework for random component failures, to better be able to evaluate our implemented views.

The mixing station window, corresponding to the Process Unit control proposed in 17, has been implemented based on the given GUI. Mainly, we augmented it with an Alarm & Event widget that displays pertinent information about the operation of the mixing station. Each entry in it corresponds to a current alarm or event in one of the tanks of the mixing station.

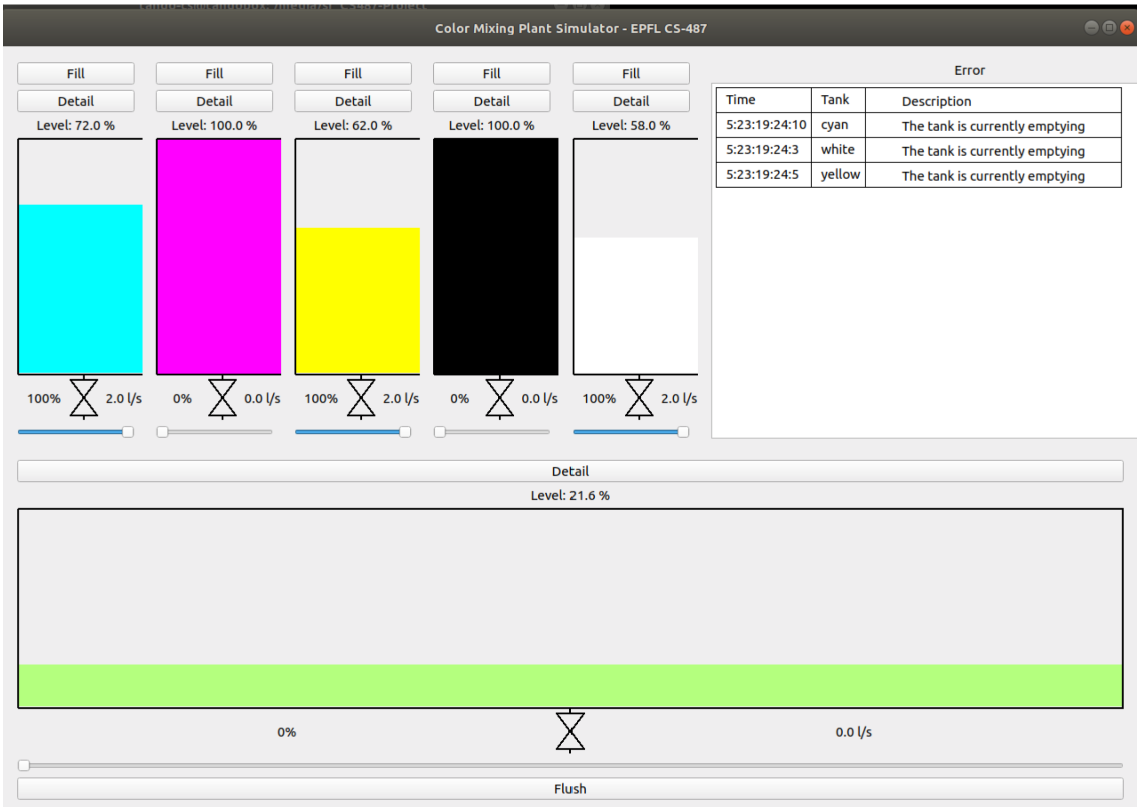

Figure 19: Implemented Process Unit Control

Our second graphic implementation is the Process Unit Detail view, which contains information about a single paint tank. This view corresponds to the proposed one in 18. The same Alarm & Event widget as for the PUC is re-used here, but now only showing entries about the one paint tank.

In order to maintain accuracy in the simulated alarms & events displayed by the widget, the simulator augmentation was done in two levels. At the base, a framework for random component failures was implemented. A failure is intended to be known only to the simulation itself. It results in a failed sensor returning random values, and a failed actuator simply not doing anything. Figure 21 shows the plant in faulty operation, with all paint tank color sensors as well as the yellow (middle) tank valve having experienced failures.

To properly mirror the proposed sensor usage in error detection, a separate frame-

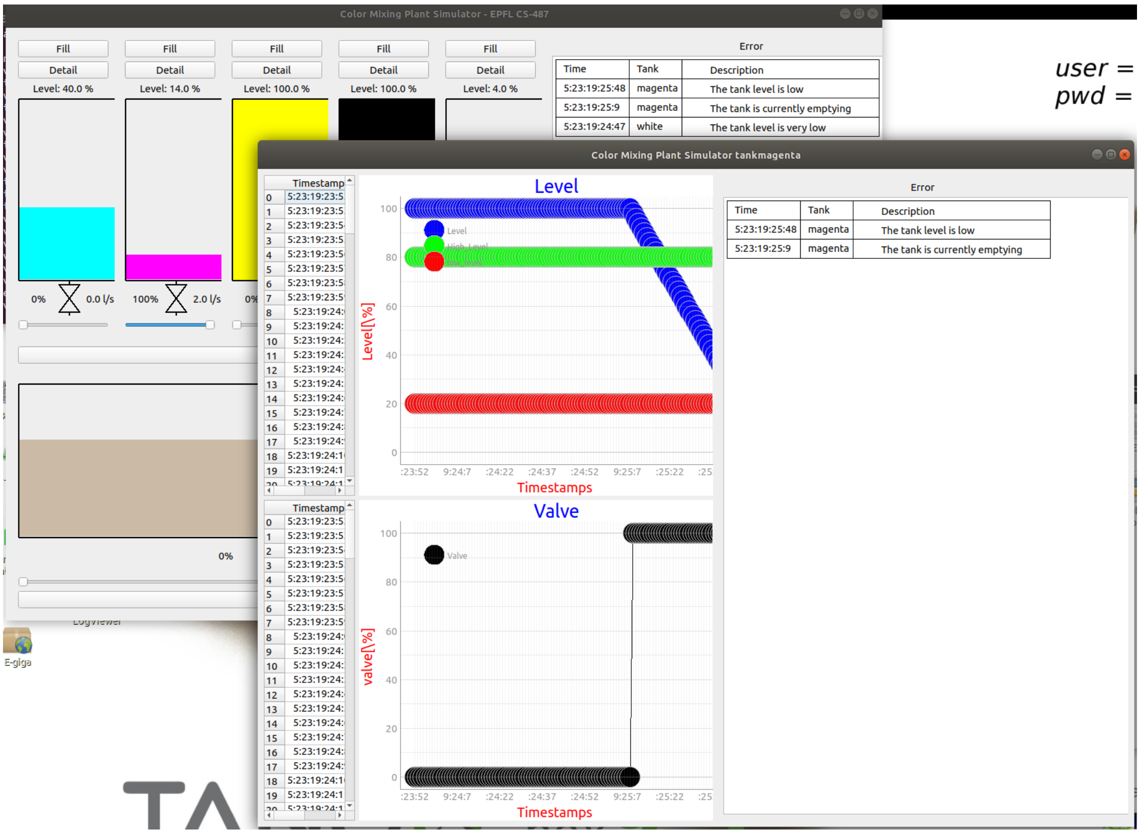

Figure 20: Implemented Process Unit Detail

work uses readings of the sensors, functioning or broken, to detect alarms & events that should be displayed in the widget. For instance, the case in Figure 21 results in two listed alarms/events for the yellow tank. The 'Level stagnation' alarm is the result of a discrepancy between sensors: the valve sensor is reporting as 100% open, while the outflow sensor is reporting no flow. These conflicting readings result in the alarm. Secondly, the event 'The tank is currently emptying' is also shown, which in this situation is a result of a faulty reading by the malfunctioning level sensor, and a correct reading from the level sensor. Simply put, when the valve is open and the tank contains paint, it should currently be emptying. As the supervision system doesn't in fact *know* if a component as failed or not, it displays this event based on the sensor readings it has.

As the figures here only display a part of the implementation in code, the reader may visit the project's GitHub repository, see Section 6, to find more figures as well as video clips of the plant in both proper operation and while suffering from malfunctions.

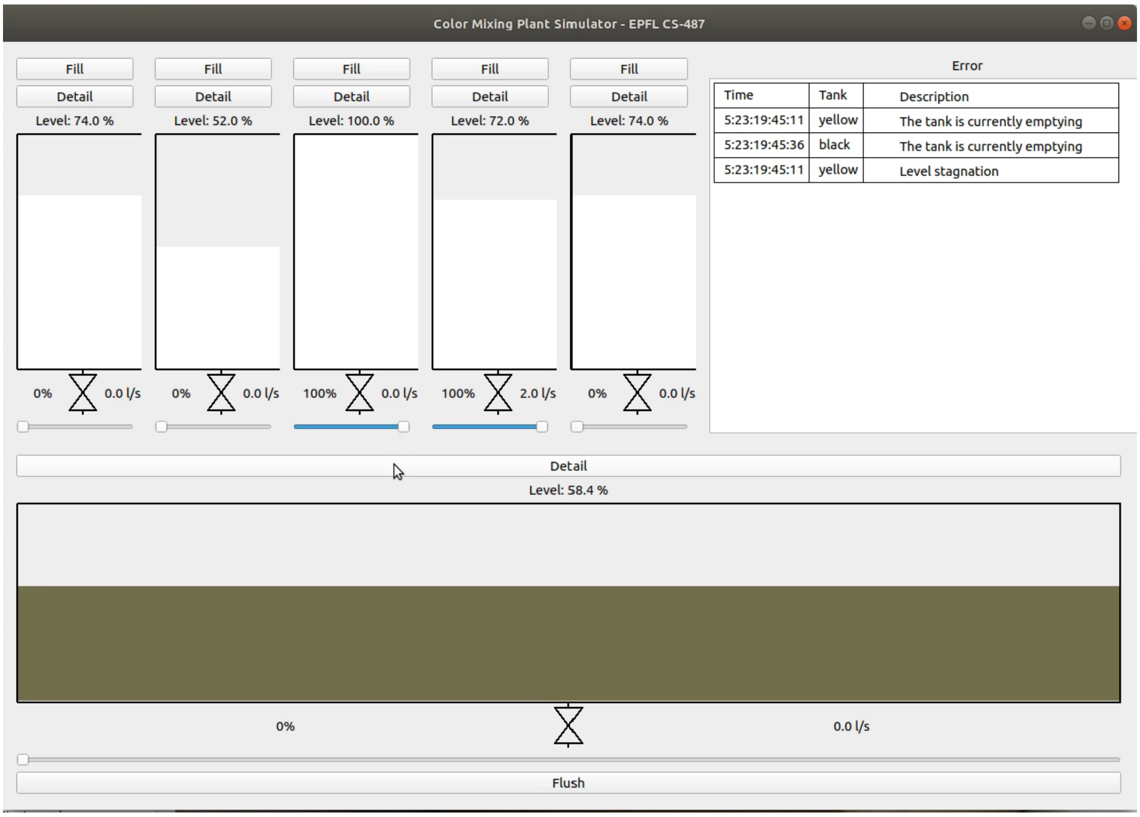

Figure 21: Process Unit Control, with component failures

4 Qualitative Dependability Analysis

We will consider each component of the single mixing station system. The station is made up of 3 main parts: color tanks, mixing tank and the control system. Color tanks have output valves, sensor to detect flow, sensors to detect color levels. Mixing tank has an output pump, sensors to detect flow, sensors to detect its level.

4.1 Fault Tree Analysis (FTA)

To perform FTA, the following steps are followed.

4.1.1 Top-level events

First we identify the top-level event which is production error or safety risk. 3 top level events are identified in this case.

1. The mixing tank does not receive the correct color of a paint mixture.
2. The mixing tank overflows.
3. The mixing tank doesn't receive enough paint as requested.

4.1.2 Intermediate and basic events

Next, we identify the potential causes or contributing factors that can lead to each primary event. Intermediate and basic events and how they relate to each other are presented in Fig. 22
Now, we have identified the basic events which cause of the top undesired and severe events which could happen. These basic events can be further analyzed for their potential causes and consequences and appropriate measures can be taken to reduce the likelihood and impact of failures.

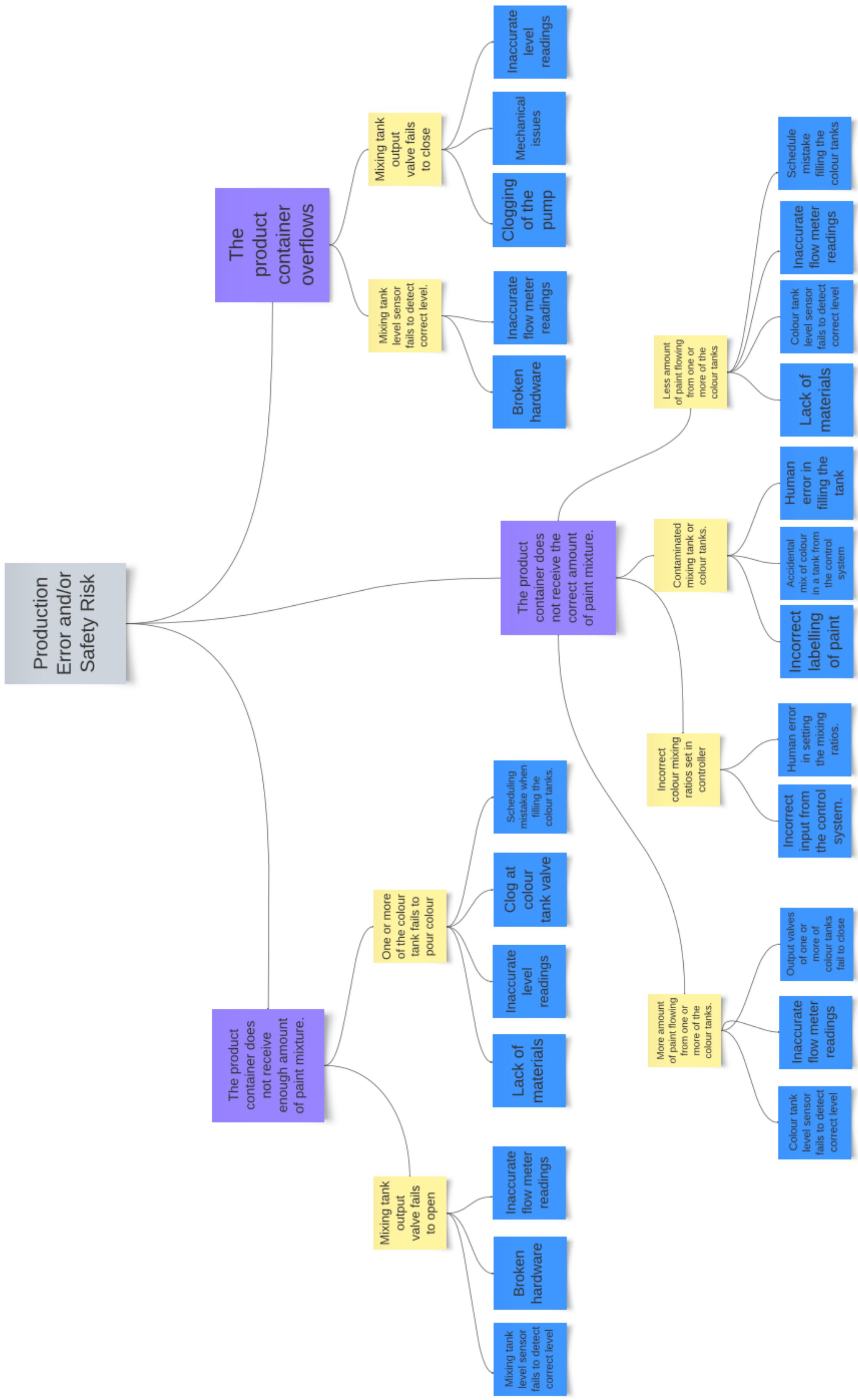

Figure 22: Fault Tree Analysis

4.2 Failure Modes and Effects Analysis (FMEA)

We also perform FMEA, as presented in Table 8. For each component of the system, we analyse the function they play, failure modes, effect of their failure and how its detection can be detected. Necessary actions depending on the criticality of a failure can be taken.

Now that we have inspected the failure modes and their effects for each potential failure mode, to improve the reliability and robustness of the production plant, the focus would be to mitigate the risks of potential failure modes with the highest criticality. For example, to lower the risk of failure mode which the color tanks' output valves failing to open or close, higher quality valves could be used and more frequent control checks can be scheduled. This is a compromise to make between working time and check time. For low criticality failure modes, it can be worth to not lose time and money to not produce.

Table 8: Table of FMEA

Component	**Specific component**	**Function**	**Failure mode**	**Failure cause**
Colour tanks	Level sensors	To detect the level of colour tank	Fails to detect correct level, inadvertent operation	Calibration issues
	Output valves	Flow of paint from colour tank to mixing tank	Fails to open, restricted flow	Hardware issues, corrosion, actuator failure, controller failure
			Fails to close	
	Flow sensors	To measure level of flow to mixing tank	Erroneous output (decreased)	Calibration issues
			Erroneous output (increased)	
Mixing tank	Mixing propeller	To mix paint in mixing tank	Premature operation	Power supply issues
	Level sensor	To detect the level of colour tank	Erroneous output	Calibration issues
	Output valve	To dispense the mix to the product container	Fails to open, restricted flow	Hardware issues, corrosion, actuator failure, controller failure
			Fails to close	
	Emptying pump	To empty the tank when changing the recipe	Fails to function	Power supply issues, controller failure, mechanical issues, blockage
Control system			Fails to operate	Power outage in source

Component	**Specific component**	**Failure mode**	**Local failure effect**
Colour tanks	Level sensors	Fails to detect correct level, inadvertent operation	Incorrect amounts of paint dispensed, wrong ratios in mixing tank
	Output valves	Fails to open, restricted flow	No paint dispensed
		Fails to close	More than required paint dispensed, incorrect ratios and mixing tank overflowing
	Flow sensors	Erroneous output (decreased)	More than required paint dispensed, incorrect ratios and mixing tank overflowing
		Erroneous output (increased)	Not enough paint dispensed, incorrect ratios
Mixing tank	Mixing propeller	Premature operation	Uneven production, unreliable quality and faulty products.
	Level sensor	Erroneous output	incorrect amount of paint into the product container
	Output valve	Fails to open, restricted flow	Not enough paint dispensed
		Fails to close	More than required paint dispensed, and product container overflow
	Emptying pump	Fails to function	Contamination of the mixing tank for subsequent recipes
Control system	-	Fails to operate	Erroneous inputs and output boards, failure of the whole process

Component	Specific component	Failure mode	Global failure effect	Detection
Colour tanks	Level sensors	Fails to detect correct level, inadvertent operation	Faulty products	Discrepancy between continuous and discrete level sensors
	output valves	Fails to open, restricted flow	Production error, Faulty products	By inspecting the flow sensor or level sensor, or level sensor of mixing tank
		Fails to close	Safety hazard, production error, Faulty products	
	flow sensors	Erroneous output (decreased)	Safety hazard, production error, Faulty products	Discrepancy between flow sensor reading and expected flow based on current and previous level readings
		Erroneous output (increased)	Production error, Faulty products	
Mixing tank	Mixing propeller	Premature operation	Production error	Discrepancy between the drawn current and the expected value
	Level sensor	Erroneous output	Production error	Discrepancy between continuous and discrete level sensors
	Output valve	Fails to open, restricted flow	Production error	Discrepancy between level sensor and expected level
		Fails to close	Production error, safety error	
	Emptying pump	Fails to function	Production error, safety error	Outflow slower than expected
Control system		Fails to operate	Production error, safety error	Noticed immediately

5 Conclusion

To make a proposal of a paint production plant made of four mixing stations, we have first determined the key signals and alarms to use, then established a detailed list of components and of the control architecture needed to implement the automation of the plant, conceived and tested the graphical interface along with component failure simulations, and to finish evaluated the plant through a dependability analysis performing a fault tree and a failure mode and effects analysis. This is how we result with a proposition to answer the problem of implementing an automatized color mixing plant.

This is an interesting project to introduce us to the conceptualization of an automated plant, while experiencing each step of the proposition implementation. We also get an opportunity to apply the theory seen in class and have some reflection on it.
We learned the importance of doing these type of projects in a systematic and ordered way, as it is important to understand well the problem and the physical system constraints to determine the inputs and outputs of the system, and the needs of the system, such as safety and which variables we need to monitor, this way the sensor, control and SCADA devices can be selected properly, having a well-defined architecture to have a complete list of devices with specifications.

It would also be interesting to implement the automated plant in a full real physics simulation to be able to evaluate its conception.

6 References

Figure 1 from lesson CS-487 Industrial Automation.
`https://moodle.epfl.ch/pluginfile.php/1553469/course/section/268231/IA_Project_2023.pdf?time=1678178905836`,
references.bib

SCADA Systems:

- SCADA - Technical requirements from online website SCADAnow online.
- SCADA System Recommendations from online website VTSCADA.
- Clear SCADA Hardware Recommendations from online website Schneider electric comunity forum.

Implemented software:

- Project GitHub repository.
- Given sample code GitHub repository

Device List:

- LMC410 point level sensor from online website of IFM with datasheet Datasheet.
- EVC006 Cables for sensors to PLC from online website of IFM with datasheet Datasheet.
- PS307A continous level sensor from online website of IFM with datasheet Datasheet.
- LMC410 continous flow sensor from online website of IFM with datasheet Datasheet.
- 60E-CPN-2M3NI2NO CPXE PLC from online website of Festo with datasheet Datasheet.
- CACN-3A-1-20-G2 Power Supply from online website of Festo with datasheet Datasheet.
- C2653937 KVZB ball valvle actuator with controller from online website of Festo with datasheet Datasheet.
- PUN-H-6X1-BL plastic tubing for compressed air from online website of Festo with datasheet Datasheet.
- MSB6-1/2:C3:J1-WP Air Preparation unit for compressed air from online website of Festo with datasheet Datasheet.
- ACS310 Frequency variator for pumps and fans from online website of ABB with datasheet Datasheet.
- Rotomax II 420 RMAX Propeller for mixing applications in tanks with 3 blades and motor from online website of ADMIX with datasheet Datasheet.
- DM06P-SD3NU071M Centrifugal pump for mixing basin from online website of DEBEM with datasheet Datasheet.
- RS2R Interlock switch for gates from online website of EATON with datasheet Datasheet.
- FL SWITCH 1005N - Industrial Ethernet Switch from online website of Phoenix Contact with datasheet Datasheet.
- BL RACKMOUNT 4U - Rackmount Industrial PC for SCADA from online website of Phoenix Contact with datasheet Datasheet.
- X-22E 22 inch FHD Professional All-round Monitor for Industrial PC for SCADA from online website of AG NEOVO with datasheet Datasheet.

7 Appendix

Table 9: Table listing signals related to each mixing station 1

Signal names of mixing station 1		
input signals	output signal	alarm signals
1_very_low_tank_1	1_output_valve_0	1_very_low_1
1_very_low_tank_2	1_output_valve_1	1_very_low_2
1_very_low_tank_3	1_output_valve_2	1_very_low_3
1_very_low_tank_4	1_output_valve_3	1_very_low_4
1_very_low_tank_5	1_output_valve_4	1_very_low_5
1_low_tank_1	1_output_valve_5	1_low_1
1_low_tank_2	1_empyting_pump_0	1_low_2
1_low_tank_3	1_tank_speed_0	1_low_3
1_low_tank_4		1_low_4
1_low_tank_5		1_low_5
1_high_tank_1		1_very_high_0
1_high_tank_2		1_empty_0
1_high_tank_3		1_empty_1
1_high_tank_4		1_empty_2
1_high_tank_5		1_empty_3
1_very_high_tank_0	Interlock	1_empty_4
1_very_high_tank_1	1_emptying_tank_0	1_empty_5
1_very_high_tank_2	1_max_level_tank_0	1_emptying_process_0
1_very_high_tank_3	1_secure_operation_0	1_emptying_process_1
1_very_high_tank_4	1_open_fence_process_stop	1_emptying_process_2
1_very_high_tank_5	1_high_leakage_process_stop	1_emptying_process_3
1_outflow_tank_0	1_motor_stall_process_stop	1_emptying_process_4
1_outflow_tank_1		1_emptying_process_5
1_outflow_tank_2		1_leak_0
1_outflow_tank_3		1_leak_1
1_outflow_tank_4		1_leak_2
1_outflow_tank_5	alarm signals	1_leak_3
1_level_tank_0	1_level_conflict_1	1_leak_4
1_level_tank_1	1_level_conflict_2	1_leak_5
1_level_tank_2	1_level_conflict_3	1_level_stagnation_out_0
1_level_tank_3	1_level_conflict_4	1_level_stagnation_out_1
1_level_tank_4	1_level_conflict_5	1_level_stagnation_out_2
1_level_tank_5	1_level_stagnation_in_01	1_level_stagnation_out_3
1_mixer_current_1	1_level_stagnation_in_02	1_level_stagnation_out_4
1_mixer_current_2	1_level_stagnation_in_03	1_level_stagnation_out_5
1_door_open	1_level_stagnation_in_04	
	1_level_stagnation_in_05	

Table 10: Table listing signals related to each mixing station 2

Signal names of mixing station 2		
input signals	output signal	alarm signals
2_very_low_tank_1	2_output_valve_0	2_very_low_1
2_very_low_tank_2	2_output_valve_1	2_very_low_2
2_very_low_tank_3	2_output_valve_2	2_very_low_3
2_very_low_tank_4	2_output_valve_3	2_very_low_4
2_very_low_tank_5	2_output_valve_4	2_very_low_5
2_low_tank_1	2_output_valve_5	2_low_1
2_low_tank_2	2_empyting_pump_0	2_low_2
2_low_tank_3	2_tank_speed_0	2_low_3
2_low_tank_4		2_low_4
2_low_tank_5		2_low_5
2_high_tank_1		2_very_high_0
2_high_tank_2		2_empty_0
2_high_tank_3		2_empty_1
2_high_tank_4		2_empty_2
2_high_tank_5		2_empty_3
2_very_high_tank_0	Interlock	2_empty_4
2_very_high_tank_1	2_emptying_tank_0	2_empty_5
2_very_high_tank_2	2_max_level_tank_0	2_emptying_process_0
2_very_high_tank_3	2_secure_operation_0	2_emptying_process_1
2_very_high_tank_4	2_open_fence_process_stop	2_emptying_process_2
2_very_high_tank_5	2_high_leakage_process_stop	2_emptying_process_3
2_outflow_tank_0	2_motor_stall_process_stop	2_emptying_process_4
2_outflow_tank_1		2_emptying_process_5
2_outflow_tank_2		2_leak_0
2_outflow_tank_3		2_leak_1
2_outflow_tank_4		2_leak_2
2_outflow_tank_5		2_leak_3
2_level_tank_0		2_leak_4
2_level_tank_1		2_leak_5
2_level_tank_2		2_level_stagnation_out_0
2_level_tank_3		2_level_stagnation_out_1
2_level_tank_4		2_level_stagnation_out_2
2_level_tank_5		2_level_stagnation_out_3
2_mixer_current_1		2_level_stagnation_out_4
2_mixer_current_2	alarm signals	2_level_stagnation_out_5
2_door_open	2_level_conflict_1	2_level_stagnation_in_01
	2_level_conflict_2	2_level_stagnation_in_02
	2_level_conflict_3	2_level_stagnation_in_03
	2_level_conflict_4	2_level_stagnation_in_04
	2_level_conflict_5	2_level_stagnation_in_05

Table 11: Table listing signals related to each mixing station 3

Signal names of mixing station 3		
input signals	output signal	alarm signals
3_very_low_tank_1	3_output_valve_0	3_very_low_1
3_very_low_tank_2	3_output_valve_1	3_very_low_2
3_very_low_tank_3	3_output_valve_2	3_very_low_3
3_very_low_tank_4	3_output_valve_3	3_very_low_4
3_very_low_tank_5	3_output_valve_4	3_very_low_5
3_low_tank_1	3_output_valve_5	3_low_1
3_low_tank_2	3_empyting_pump_0	3_low_2
3_low_tank_3	3_tank_speed_0	3_low_3
3_low_tank_4		3_low_4
3_low_tank_5		3_low_5
3_high_tank_1		3_very_high_0
3_high_tank_2		3_empty_0
3_high_tank_3		3_empty_1
3_high_tank_4		3_empty_2
3_high_tank_5		3_empty_3
3_very_high_tank_0	Interlock	3_empty_4
3_very_high_tank_1	3_emptying_tank_0	3_empty_5
3_very_high_tank_2	3_max_level_tank_0	3_emptying_process_0
3_very_high_tank_3	3_secure_operation_0	3_emptying_process_1
3_very_high_tank_4	3_open_fence_process_stop	3_emptying_process_2
3_very_high_tank_5	3_high_leakage_process_stop	3_emptying_process_3
3_outflow_tank_0	3_motor_stall_process_stop	3_emptying_process_4
3_outflow_tank_1		3_emptying_process_5
3_outflow_tank_2		3_leak_0
3_outflow_tank_3		3_leak_1
3_outflow_tank_4		3_leak_2
3_outflow_tank_5		3_leak_3
3_level_tank_0		3_leak_4
3_level_tank_1		3_leak_5
3_level_tank_2		3_level_stagnation_out_0
3_level_tank_3		3_level_stagnation_out_1
3_level_tank_4		3_level_stagnation_out_2
3_level_tank_5		3_level_stagnation_out_3
3_mixer_current_1		3_level_stagnation_out_4
3_mixer_current_2	alarm signals	3_level_stagnation_out_5
3_door_open	3_level_conflict_1	3_level_stagnation_in_01
	3_level_conflict_2	3_level_stagnation_in_02
	3_level_conflict_3	3_level_stagnation_in_03
	3_level_conflict_4	3_level_stagnation_in_04
	3_level_conflict_5	3_level_stagnation_in_05

Table 12: Table listing signals related to each mixing station 4

Signal names of mixing station 4		
input signals	output signal	alarm signals
4_very_low_tank_1	4_output_valve_0	4_very_low_1
4_very_low_tank_2	4_output_valve_1	4_very_low_2
4_very_low_tank_3	4_output_valve_2	4_very_low_3
4_very_low_tank_4	4_output_valve_3	4_very_low_4
4_very_low_tank_5	4_output_valve_4	4_very_low_5
4_low_tank_1	4_output_valve_5	4_low_1
4_low_tank_2	4_empyting_pump_0	4_low_2
4_low_tank_3	4_tank_speed_0	4_low_3
4_low_tank_4		4_low_4
4_low_tank_5		4_low_5
4_high_tank_1		4_very_high_0
4_high_tank_2		4_empty_0
4_high_tank_3		4_empty_1
4_high_tank_4		4_empty_2
4_high_tank_5		4_empty_3
4_very_high_tank_0	Interlock	4_empty_4
4_very_high_tank_1	4_emptying_tank_0	4_empty_5
4_very_high_tank_2	4_max_level_tank_0	4_emptying_process_0
4_very_high_tank_3	4_secure_operation_0	4_emptying_process_1
4_very_high_tank_4	4_open_fence_process_stop	4_emptying_process_2
4_very_high_tank_5	4_high_leakage_process_stop	4_emptying_process_3
4_outflow_tank_0	4_motor_stall_process_stop	4_emptying_process_4
4_outflow_tank_1		4_emptying_process_5
4_outflow_tank_2		4_leak_0
4_outflow_tank_3		4_leak_1
4_outflow_tank_4		4_leak_2
4_outflow_tank_5		4_leak_3
4_level_tank_0		4_leak_4
4_level_tank_1		4_leak_5
4_level_tank_2		4_level_stagnation_out_0
4_level_tank_3		4_level_stagnation_out_1
4_level_tank_4		4_level_stagnation_out_2
4_level_tank_5		4_level_stagnation_out_3
4_mixer_current_1		4_level_stagnation_out_4
4_mixer_current_2	alarm signals	4_level_stagnation_out_5
4_door_open	4_level_conflict_1	4_level_stagnation_in_01
	4_level_conflict_2	4_level_stagnation_in_02
	4_level_conflict_3	4_level_stagnation_in_03
	4_level_conflict_4	4_level_stagnation_in_04
	4_level_conflict_5	4_level_stagnation_in_05