Industrial Automation (CS-487)

Project: Automation System Design for a Paint Mixing Plant

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Contents

1 Introduction

This project integrates within the overarching framework of the Industrial Automation course at EPFL. The global objective is to design the monitoring and control infrastructure necessary to operate a paint production plant made of 6 mixing stations. The design of the automation architecture starts from the identification and selection of the sensors and actuators, up to the conception of the supervision system (or SCADA).

A schematic representation of each color mixing station is provided in Figure 1: they are composed of 5 color tanks (cyan, magenta, yellow, black and white) and 1 mixing basin. Each tank and basin are controlled via dedicated output valves, and they are monitored via special sensors to detect the levels and flows of paint.

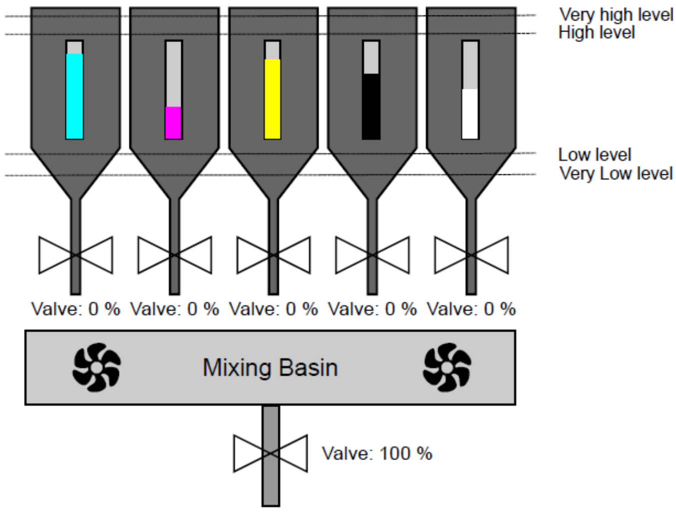

Figure 1: Schematic representation of one of the 6 color mixing stations, composed of 5 color tanks and 1 mixing basin

The report is structured as follows: first the functional analysis is performed to identify all the sensors and actuators, alarms, and interlocks. Then, the automation architecture is defined based on the functional analysis; it includes the proper selection of the PLCs and their I/O modules, the field buses, the network protocols and infrastructure, and the hardware to run the SCADA server. Subsequently, the Tango supervision control system is designed to monitor and control the whole installation. Finally, a qualitative dependability evaluation of a single mixing station is performed.

1.1 Tasks Repartition Within the Team

Everyone worked on the identification of input and output signals and on the selection of the corresponding sensors and actuators, especially Aurora, Beatrice and Riccardo. Raphaël worked on the alarms and events, while Malo focused on the interlocks. Then, Beatrice and Riccardo tackled the automation architecture section and implemented the Tango control system, defining both the back-end python code and the front-end JDraw panels. Aurora, with Beatrice and Raphaël, dealt with the design and description of the synoptic views in the supervision section. Finally, Raphaël and Malo addressed the qualitative dependability analysis.

2 Functional Analysis

The first step in the design process of the paint production plant's automation architecture consists in defining the types and ranges of sensors and actuators, the alarms to display to the plant operators, and an extensive list of interlocks and their logic. In order to make rational design decisions, some underlying assumptions concerning the system must be made. Firstly, the operating temperature of both the color tanks and the mixing basin is set to be the ambient one, namely between 18-25°C, with pressure levels remaining within 2 atm. Then, the color tanks are assumed to have a cylindrical shape, with a height of 6 m and a diameter of 2 m (thus a volume of 18 850 L), while the mixing basins have a cylindrical shape as well, with a diameter of 10 m and a height of 1.5 m (thus a volume of 117 810 L). The nominal paint flow rate is of 15 L/min, while the maximum value is set to 19 L/min (based on the specified range of the flow meter sensor selected below).

2.1 Input Signals (Sensors)

Moving on to the description of the sensors which the color tanks will be equipped with, there are:

- a **pH sensor**, specifically the PH8HS one, which is suitable for water-based paintings and is exploited to guarantee the desired viscosity for the dye. It is integrable with a 4-wire process liquid analyzer, connecting the sensors to an easy-to-read screen operation (analog input);
- a combined **temperature and humidity sensor** has been chosen to monitor the conditions inside the tank. The LF-TD 180 from Schaller is selected due to its non-invasive mounting capability, consisting of a remote sensor head and a transmitter, and the option to incorporate a display for in-field checks [7] (analog input);
- a **turbine flow meter sensor**, exploited to measure the amount of painting leaving the tank. The SF800 model from Riels Instruments is appropriate as it operates in the required ranges of temperature and pressure, and it is capable of detecting flows of up to 20 L per minute with an acceptable accuracy (analog input);
- 4 retro-reflective binary **level sensors** (P1KL002 model) to identify the very low, low, high, and very high levels inside the tank. The main advantage of these sensors is their fast response (0.14ms), their compactness, and the compatibility of their detection range with the system's dimensions (digital inputs);
- To guarantee enhanced reliability for the critical levels in particular (namely the very high and very low ones), a Endress+Hauser Micropilot FMR10 pulsed radar **level sensor**, employed to indicate the exact amount of paint left in the tanks. This sensor is ideal for challenging applications with liquids that are viscous, like paints (analog input).

Thus, there are 8 input signals for each color tank.

For what concerns the mixing basin, the same flow meter and level sensors (2 retro-reflective binary ones for high and low levels) used for the color tanks are employed. In addition to those, a sensor for measuring the **rotational speed** of the motors that mix the paint should be implemented. The capaNCDT CST6110 has been selected for this purpose because of its compact size, ease of integration, and its suitability for use in industrial environments [5] (analog input). Therefore, there are 4 input signals per mixing basin.

Finally, for each mixing station, a basic electronic vibration sensor (AV002) can be installed to provide an additional layer of assurance regarding the **system's operation**. This selected sensor may come equipped with a LED display, offering a convenient way for operators to visually confirm the activity of the equipment on-site [3] (digital input).

To sum up, the total number of sensors for each mixing station is 45, which, multiplied by six, gives a total of 270 input signals.

2.2 Output Signals (Actuators)

Pneumatic output valves are necessary for draining the tanks effectively. IMI SHP Positioner valves have been selected for their capability to offer remote and on-site control, which is crucial for precise quantity control and action in emergency situations [4] (analog input, analog/digital output). It is assumed that the paint tanks are emptied thanks to gravity.

For draining and dosing the paint exit from the mixing basin, the VA40 metallic pump from Verder is chosen. This pump ensures effective emptying of containers and precise liquid dosing. Specifically designed for viscous fluids like paints, it can handle fluids with viscosities up to 15 000 mPa·s, and it has a capacity to dispense 443 L per minute [6]. As it is controlled by pressurized air, an air compressor requiring an analog control signal is supposed to be connected to it, although the latter will not be taken into consideration in the plant.

Two motors are placed in the mixing basin [1], one active and the other one for cold redundancy. They are accompanied by a motion controller with an integrated Ethernet option card to communicate with the system network infrastructures [2]. Thus, there are 48 output signals in total.

2.3 Summary of Signals

Table 1 summarizes the details regarding the signal types, distinguishing between inputs and outputs, along with their respective quantities and naming conventions. The signals have a specific naming convention: the first character (x) corresponds to the station number, and the second character is either "T" for a tank or "B" for a mixing basin. Optionally, the third character represents the first letter of the paint color in the tank (c), and the fourth character, if present, denotes a number when multiple signals of the same type exist in the same location (y). Finally, the last capital letter represents the specific sensor or actuator.

Table 1: Signals types, quantities, and naming convention

Sensor / Actuator	**Signal type**	**Naming convention**	**Quantity**
pH sensor	analog input	xTcH	30
Temperature and humidity sensor	analog input	xTcT	30
Turbine flow meter sensor	analog input	xTcF or xBF	36
Retro-reflective binary level sensors	binary input	xTcyL or xByL	132
Pulsed radar level sensor	analog input	xTcR	60
Pneumatic output valves	analog/digital output	xTcV	30
Rotational speed sensor	analog input	xBS	6
Electronic vibration sensor	digital input	xE	6
Pump	analog output	xBP	6
Motors	analog output	xByM	12

2.4 Alarms and Events

An efficient implementation of events and alarms is essential to safely operate the paint mixing plant. Their number is minimized while ensuring that the occurrence of accidents or failures is avoided as much as possible. The supervision software indicates the insurgence of faults and errors; however, the deployment of alarms is reserved to imminent risks of failures requiring prompt actions from the plant operators. The exhaustive list of alarms and events is displayed in Table 2.

Table 2: Exhaustive list of alarms and events - priority levels: high (in red), medium (in orange), and low (in yellow)

nomenclature	reaction time	title & description	remedial action
Alarm 1 (A1)	10 min	motor X of station Y with no speed while the whole system is on	activate the other motor and contact the maintenance team OR repair the speed sensor
Alarm 2 (A2)	20 min	extreme paint level (very high / low) reached in tank X of station Y	stop / start filling up the tank
Alarm 3 (A3)	20 min	paint leaking from tank X or basin of station Y - flow meter detects paint flow while the whole system is off	contact the maintenance team to fix the leak OR repair the sensors
Alarm 4 (A4)	20 min	paint leaking out of the system from pump of tank X of station Y - tank's valve is open but basin's level sensors don't detect any paint	contact the maintenance team to fix the pump OR repair the basin's sensors
Alarm 5 (A5)	60 min	anomalous temperature in tank X of station Y - outside the range 10-35°C	activate the heating or cooling system (if any) OR turn off the system
Event 1 (E1)	60 min	Maximum paint flow rate reached (19 L/min) in tank X or basin of station Y	reduce the corresponding output valve's opening to reduce the paint flow
Event 2 (E2)	60 min	motor X of station Y over speeding ($>$ 1000 rpm)	reduce the motor's rotational speed
Event 3 (E3)	210 min	high or low level reached in tank X of station Y	stop or start filling up the tank
Event 4 (E4)	24 h	principal and redundant level sensors of tank X of station Y indicate different values	contact the maintenance team to replace the faulty sensor(s)

Concerning the reaction times, some additional assumptions have to be made. Firstly, by placing the low and very low (resp. high) retro-reflective binary level sensors at 1.0 and 0.1 m from the bottom (resp. top) of the tanks, and given the nominal paint flow rate of 15 L/min, the reaction times of event 3 and alarm 2 are of 210 and 20 minutes respectively, after which the tanks would be completely empty (resp. full). For the alarms 3 and 4, which sound whenever paint leaks are detected, the reaction times are set to 20 minutes as well, assuming that the paint's level is currently very low.

The rest of the alarms are set more arbitrarily: 10 minutes are required to notice that the motors are not working (alarm 1, considered to be of high importance as the various colors have to be properly mixed to obtain the desired color at the mixing station's output), and 60 minutes are retained enough to fix the paint's temperature (alarm 5), and to reduce the paint flow rate (event 1) or the motor's speed (event 2). Finally, 24h is considered as a reasonable amount of time for the operators to fix or replace the faulty (redundant) sensors (event 4).

2.5 Interlocks

An interlock system is a type of safety mechanism designed to prevent reaching undesired states in a machine or work environment, ensuring that certain conditions are met before a process can proceed. The key components of an interlock system include sensors, actuators, and control logic; the latter integrates the inputs from the sensors and commands the actuators accordingly.

The design of the interlock system of the paint production plant is displayed in Figure 2. It is checking that safety and quality are maintained at any time, based on the set of events and alarms established in the previous section.

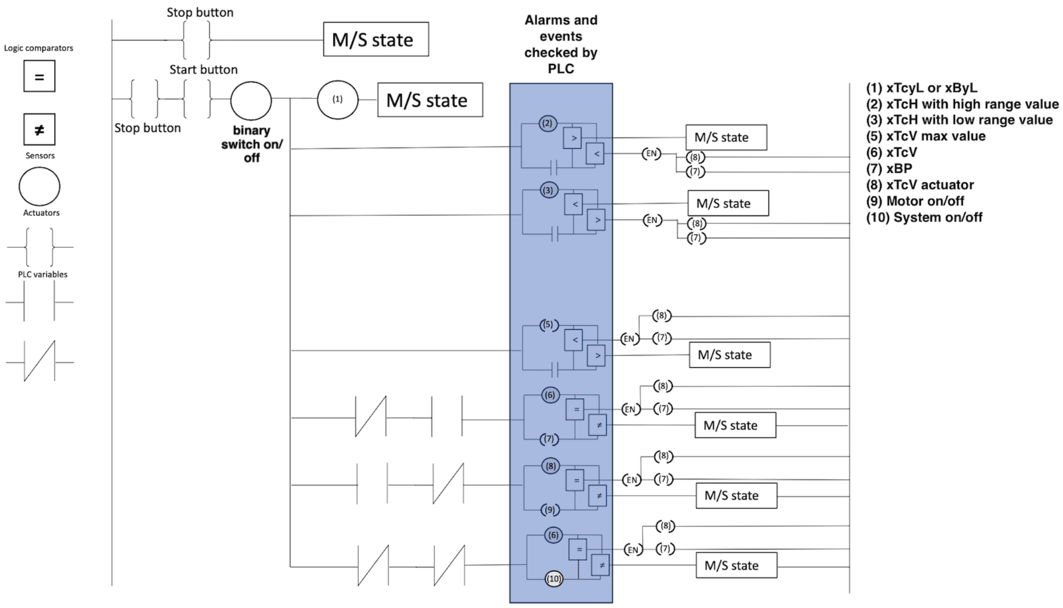

Figure 2: Automation interlock system of the paint production plant

3 Automation Architecture

3.1 Architecture Overview

Starting from the lower level, sensors and actuators are connected to PLCs in two ways:

1. analog devices: directly to the PLC;
2. digital devices: to an IO-Link master. The IO-Link master is then connected to the PLC through a field bus (Ethernet).

Each mixing station is equipped with two PLCs, each operating independently of those in the other stations. The connection between PLCs and the SCADA system will be explored later on.

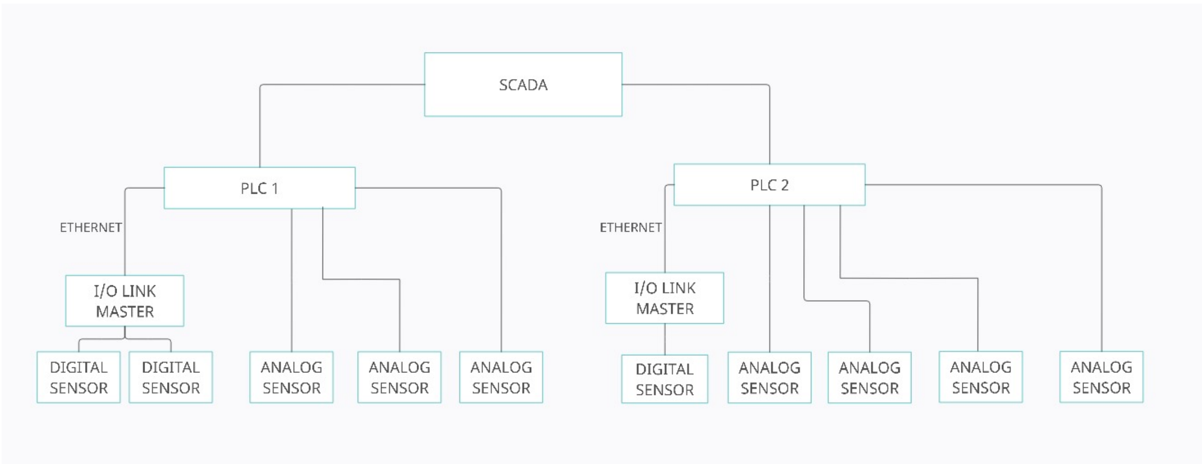

Figure 3: Schematic representation of the automation architecture of one mixing station - IO-link masters will not be used in the final implementation (only used in case of need of expansion)

To ensure a smooth operation of the entire facility, selecting the appropriate power supply is a crucial choice to make. The selected unit delivers a consistent 24V output, capable of supporting substantial output power requirements.

3.2 Programmable Logic Controllers

Diving into the architecture of a mixing station, on the sensor level, a division in two groups was created, each group referencing to a single PLC:

1. **PLC 1 connections:**
   - level sensors of the tank [digital input]: 4 (x5 tanks);
   - level sensors of the mixing basin [digital input]: 2;
   - temperature & humidity sensor [analog input]: 1 (x5 tanks);
   - pulsed radar level sensor [analog input]: 1 (x5 tanks);
   - ph sensor [analog input]: 1 (x5 tanks).

   Model: PLC 1 will be an ABB AC500-eco composed by:

   - CPU: PM5012-R-ETH with 6DI 4DO, using relay. Outputs are actually not needed, so output technology is not important in this case, as this PLC only has to collect data from the sensors;
   - 1 digital expansion module DI562: each with 16DI;
   - 4 analog modules AI561: each with 4AI, compatible with 4-20mA.

2. **PLC 2 connections:**
   - motors [digital output, digital input for encoder]: 2 (x5 tanks);

- flow meter of the tank [analog input]: 1 (x5 tanks);
- flow meter of the mixing basin [analog input]: 1;
- valve of the tank [analog output, digital input for position]: 1 (x5 tanks);
- pump of the mixing basin [analog output]: 1.

Model: PLC 2 will be an ABB AC500-eco composed by:

- CPU: PM5072-T-2ETHW with 12DI 8DO;
- 1 digital expansion module DI561: with 8 extra DI;
- 2 analog expansion modules AI561: each with 4 extra AI.

The potential integration of RTUs was evaluated, but given the moderate distances within the plant and the controlled environmental conditions, it was determined that their inclusion might not offer significant advantages.

3.3 Fieldbuses

PLC 1 and PLC 2 are not connected to each other. This architecture was designed taking into consideration that, even in a critical scenario with a high level alarm, the allowed reaction time is always large enough to guarantee the additional intermediate step through the SCADA system.

For what concerns the signal flow, the values coming from the sensors are acquired by the two PLCs according to the above described distinction. As the distance between the sensors and the PLCs is of the order of tens of meter, they are connected directly to the PLCs.

The use of an IO-Link was evaluated and discarded, being the number of digital signals low enough. In this way, the infrastructures' complexity was not increased. However, in case of expansion this solution could be reevaluated. In fact, the chosen digital level sensors are compatible with an IO-Link transmission. Moreover, the short distance between the sensors and the master required for correct functioning (20m) would be satisfied as well.

Then, the PLCs elaborate the data and transmit them to the SCADA system. The signal flow is analogous for all the 6 mixing stations.

3.4 Network Infrastructure

3.4.1 Requirements

Because of the limited distances (< 20m) between components in the mixing stations, and (< 100m) between the latter, it was determined that wireless connections would not be relied upon, and instead, operations would be conducted via wires. This would ensure higher reliability for both data signals and safety commands.

3.4.2 Timing Requirements

In terms of timing strategy, the operation of PLC1 is designated to be event-driven to minimize unnecessary overhead on communication links. Specifically, level sensors will change their value after large time intervals, making a cyclic read of their values inefficient. This decision is further reinforced by generous timing allowances available for addressing critical events associated with the sensors' values, such as unusually high temperatures or abnormal paint levels. Concerning the amount of information, it is extremely low, being all the signals simply on/off states.

For PLC2, a cyclic operation was selected considering the higher amount of information that is received. Indeed, a continuous monitoring is essential to finely adjust the valves' aperture, ensuring the correct coloration in the basin, as well as maintaining the appropriate mixing speed. The probing time will be one every 2 minutes. Even under the most extreme circumstances, where the flow rate reaches 19L/min and the liquid level is at its highest or lowest, the quantity of liquid needed to cause system failure is 314L. To conclude, no strict real time requirement operation is needed in the designed system.

3.4.3 Communication Equipment

The chosen PLCs' CPU have an Ethernet port, allowing the designed connection to the SCADA hardware.

3.5 SCADA Hardware

To control the chosen PLC, the ABB Software Platform Automation Builder needs to be employed. The hardware architecture is then constituted of a Personal Computer, compliant with the following specifications to support the ABB Software: it must be running on Windows 11, it must have a minimum frequency of 1 GHz, a minimum of 4 GB RAM, and between 5 and 18 GB of free disk space. It must also be equipped with an Ethernet Port.

The SCADA systems of the mixing stations are not connected to each other, but they merge on a pyramidal structure creating a production control layer and a final main monitoring station, as illustrated in Figure 4.

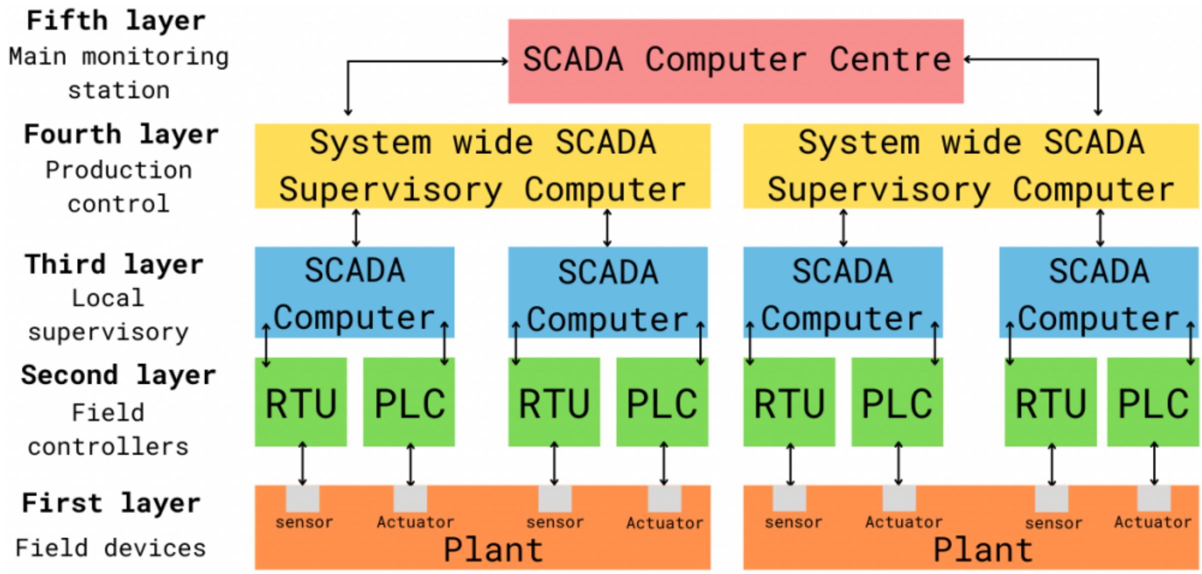

Figure 4: SCADA layers

4 Supervision

4.1 SCADA Software Architecture

The implementation of the SCADA software architecture involves generalizing the components and functionalities of the primary distributed object, namely the single paint station, into a single device. Each tank is an instance of this device. Within this framework, sensors (level, flow, pH, temperature), which primarily display state variables, are represented as attributes of the instance, while actuators (valves and pumps) are represented as commands within the device. The expected behavior of the monitoring and control application is for the end user (client) to request Tango devices to execute commands and to read or write one of their attributes.

In the Mixing Station project, a device server is responsible for the PaintTank class, which acts as a template for a paint tank. For each mixing station, six PyTango device instances are created and registered with the following identifiers: epfl/stationX/cyan, epfl/stationX/magenta, epfl/stationX/yellow, epfl/stationX/black, epfl/stationX/white, and epfl/stationX/mixer, where X can be any number from 1 to 6. This means that there are six mixing stations, each containing six device servers, all visible in Jive. The client is implemented in an object-oriented Python environment, connecting a station with six paint tanks to the corresponding Tango device instances. Commands such as setValve(), flush(), and fill() are executed to interact with the underlying attributes and methods of the Tango system.

The **HMI (Human-Machine Interface)** of Figure 7 and Figure 8 was built by leveraging JDraw and Taurus software. JDraw's drawing tool allowed to insert both interactive and non-interactive elements. Interactive elements were chosen among the "ATK Swing" group, including for example the 'Number Scalar Wheel Editor', which gives the operator control over the valve aperture of each tank, or the JDBar which represents the tank behavior.

All scalar variables were perfectly integrated in both views (PH, temperature, time until empty, level, and so on), whilst not all writing commands appears to be working: buttons are not able to actually perform their action (such as fill or flush), nor graphs to represent lines. This problem was thoroughly investigated, and it appeared to be in the end Taurus' software fault. Not all objects available in JDraw are compatible with the latter indeed. For this reason, the last steps of the process involving building the application with 'taurus newgui' were unsuccessful as well. As Figure 5 below shows, the non-compatibility issues are evident.

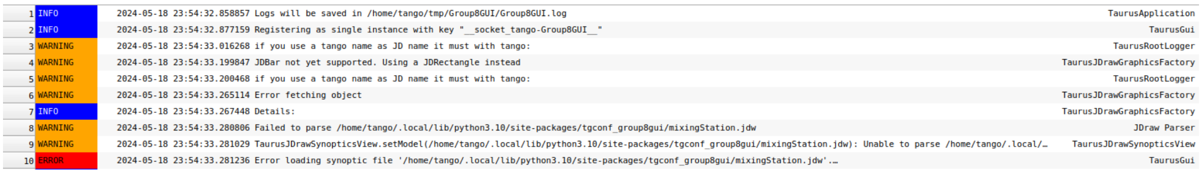

Figure 5: Taurus-JDraw non compatibility issues

4.1.1 Instructions for Running the Synoptic Views

The following scripts must be run in order to properly use the synoptic views:

1. *PaintMixingStation.py* on a specific station;

2. *gui_ old.py*: this is the HMI provided as starting point. It is needed only to run fill/flush commands, as these are not functioning in the two views as it was explained above;

3. *JDraw*: to open the .jdw files [*mixingStation.jdw*, *paintTank.jdw*] and simulate them inside the 'Tango Synoptic View'.

4.1.2 Additional Considerations

Despite consistent efforts, the integration of the writing commands was unsuccessful. Similarly, the dynamic change of the mixing basin paint color based on the input of an RGB color string could not be implemented.

In the synoptic view of Figure 8, Ph and temperature variables were coded to be subject to little random changes, in order to better represent real scenario in which they would not be constant. Concerning the 'time until empty' field, it actually displays an algebraically calculated value, which changes depending on the tank level and on the valve aperture. It is only important to notice that the 'minutes' unit of measure reported in the view actually correspond to seconds in real life.

4.2 Synoptic Views

The SCADA system of the paint mixing plant is structured into three main synoptic views, adhering to hierarchical principles. The first panel provides a comprehensive overview of the entire plant, focusing on general information regarding all six mixing stations. Upon selecting a station, the second view displays a more detailed description of activities inside it, highlighting specific details of the five tanks and the mixing basin. The third and final synoptic view is conceived for an even closer monitoring of the tanks' and basin's behaviors. The idea behind the design of each synoptic view is to simplify a complex system, like the paint mixing plant, to enable the operators and technicians to efficiently identify the relevant information on the system, and make quick and guided decisions.

4.2.1 Process Area Overview

Figure 6 depicts the high-level synoptic view. In the upper part of the panel, six mixing stations are represented by a white rectangle containing six horizontal bars. The first five bars represent the levels of the five tanks in the station, colored in gray to avoid distracting the operator, as the color of the paint inside is known and not relevant in this view. The bottom bar indicates the level of the mixing basin. It was decided to display the levels of paint in each tank to provide a general overview of the entire plant. When very low or high levels are reached (indicated by vertical dotted lines), the bars turn red to catch the operator's attention (as shown in Figure 6). This way, the operator can easily notice where the problem is and can later obtain more information from the Alarms/Events table, which will be explained later. Only the mixing basin bar is colored, as it depends on the specific mix, with its color also displayed as text for clarity. This helps to keep the focus on important alarms and signals, reducing distractions. Additionally, the filling percentage of the mixing basin at each station is displayed. In the center, more generic information concerning each mixing station is present. Among them, there are the operational states of the stations (whether it is ON or OFF), when was the last maintenance performed (information that is useful for the operator to schedule in advance maintenance operations before defective behaviors occur), and for how long the mixing station has been operative.

The bottom part of the view is fully dedicated to the display of alarms and events. This was decided to provide ample space to display them, as this is the view that will be looked at most of the time and it shows information about the entire plant. The alarms and events are displayed in a tabular form, providing information on when they were generated, their level of priority, where the issues are located, and a brief description of the malfunctioning. According to the different priority levels, the line in the table will be highlighted with a bright, saturated color to catch the attention of the operator; moreover, when the alarm is related to a critical situation that could endanger the system's operation, it is also accompanied by an acoustic signal. It is important to point out that the colors chosen for the background and the labels are soft, and no fancy animation or 3D object are present in the view to avoid distracting the operators. By clicking on the button named "MSx" (where x is the number related to the mixing station), located at the top of the panel, it is possible to enter the second synoptic view. The button was colored in light blue to differentiate it from the background, without drawing too much attention.

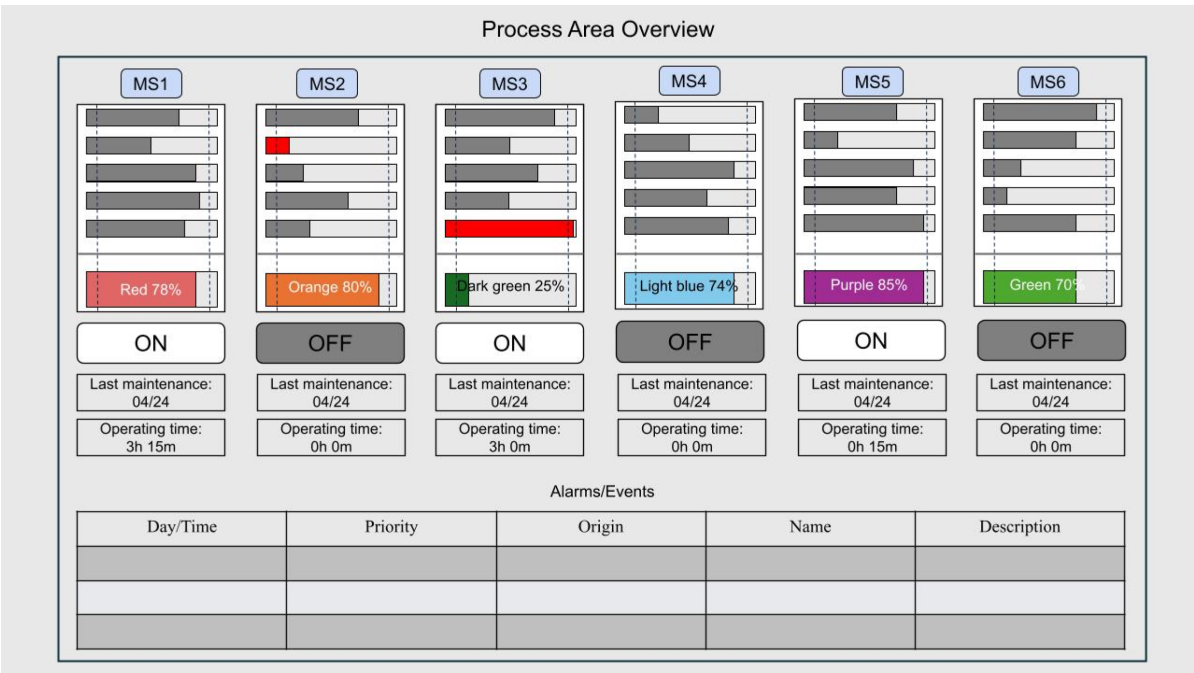

Figure 6: Process area overview

4.2.2 Process Unit Control

Figure 7 depicts the elements composing the individual mixing station. The five tanks containing the primary colors are stylized as rectangles. The tanks are colored according to the paint they contain, with the color also labeled in text for added clarity. At the top, the percentage of the paint level in the tank is displayed. On top of each tank, there is also a "fill" button that the operator can activate when the level is too low, as well as a light blue button to access the specific tank. On the left-hand side of the tank, the levels very high, high, low, and very low are highlighted as dotted lines, to ease the identification of critical situations. The same representation is used to describe the mixing basin, with the only addition of the "flush" button to empty it, and a similar button to the ones for the tanks to access the view for the basin is implemented. For each tank, the flow rate measured by the flow meter is displayed in liters per minute.

The right-hand side of the panel is dedicated to the visualization of the level trends inside the five tanks (each line colored with the corresponding paint, accompanied by a label), in one plot, the level trends inside the mixing basin, on a different plot for more clarity. It was decided to provide these plots with trends because they offer useful information to the operator about how quickly the tanks are being emptied. Trends are indeed crucial to early anomaly detection, and performance optimization by supporting planning and informed decision-making to improve plant operations and productivity. The bottom part of the panel is dedicated to the table of alarms and events, in the same format as in the Process Area View discussed in the previous section. Lastly, an emergency button, allowing to stop all the tanks in the station simultaneously, is located on the left of the alarms/event table.

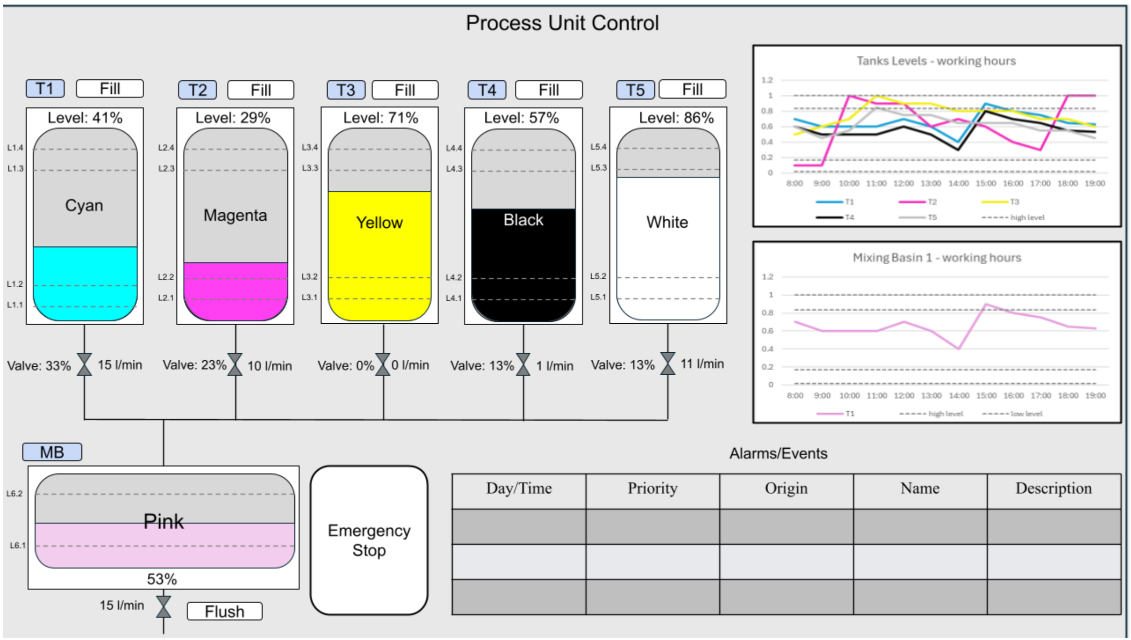

Figure 7: Process unit control

4.2.3 Process Unit Details

Lastly, Figure 8 depicts all the details concerning each single mixing tank. On the left-hand side, a bar indicating the current filling level compared with the critical ones is highlighted. Moreover, the flow rate, the valve aperture percentage, and the numerical percentage of paint level are specified. Below the representation of the tank, there is a quadrant containing additional information on the tank's state (on/off), temperature, and pH. It also shows how long it will take for the tank to be completely emptied at the current flush rate, as well as the theoretical level. This theoretical level is calculated using the known quantity of paint inside the tank and the amount of paint leaving the tank, as measured by the flow meter. This calculation is used to check if the theoretical level matches, within a certain range, the measured level. This provides an additional layer of control over the paint levels in the tanks. On the left-hand side, there are two buttons: one to fill the tank and one to flush it. The operator decides whether to fill or flush the tank, using the information from the control panel. The space below the buttons is dedicated to plotting the time evolution of the specific tank paint level, for the same reasons mentioned in subsubsection 4.2.2, and to display the alarms and events, according to the design choices previously mentioned. It is important to point out that, in the alarms and events table, an additional column named "Actions" is added. Here, there are indications and additional links to detailed documentation, aiming to direct the operator towards taking the most effective actions to minimize damages resulting from accidents.

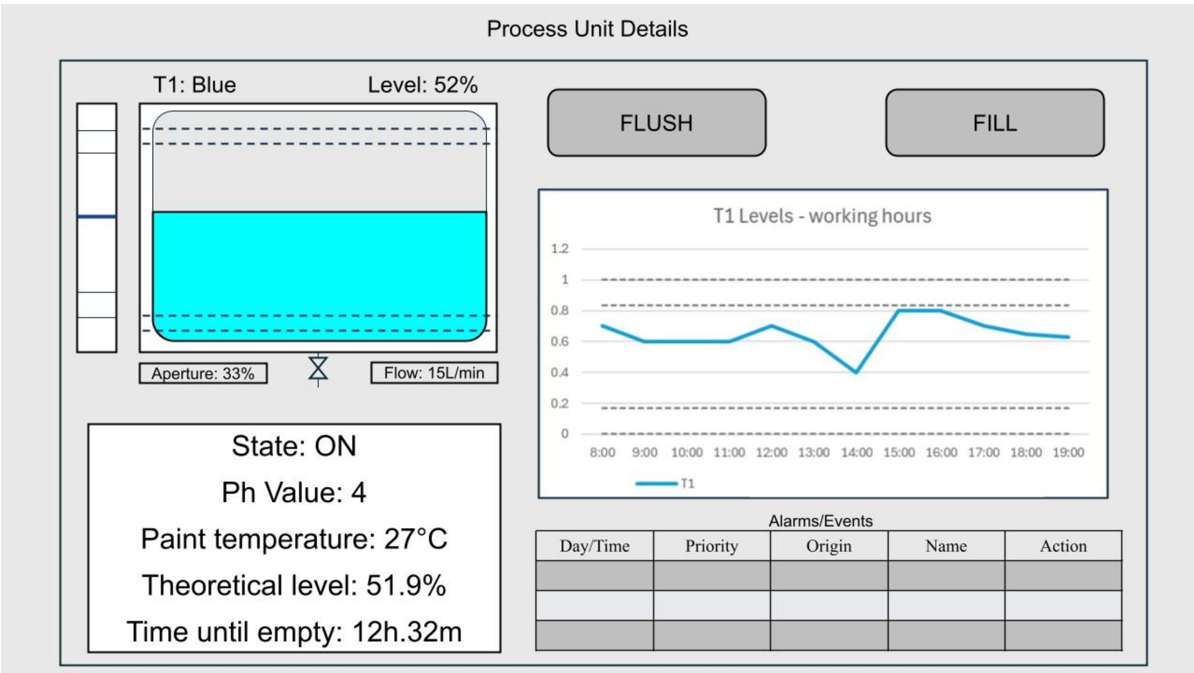

Figure 8: Process unit details

5 Qualitative Dependability Analysis

The final task of the project is dedicated to perform qualitative dependability evaluations of a color mixing station, including an FMEA and an FTA. A "failure mode and effect analysis" (or *FMEA*) is an inductive approach that aims to identify the component failures that have detrimental consequences on the system's operation in the application considered and the faults that ultimately lead to system failures. On the other hand, a "fault tree analysis" (or *FTA*) is a deductive approach that enables to point out the different combinations of conditions and components' failures that lead to a given system failure. Carrying out both approaches will contribute to having a more complete qualitative dependability analysis of the color mixing stations.

5.1 FMEA

The main steps of the FMEA consist of:

1. Breaking down the system into its main components (16 in total);
2. Identifying the contribution of each component to the system's functional structure;
3. Defining the possible failure modes of each component and their causes;
4. Explaining the effect of such failure modes on the system;
5. Providing how the failure modes can be detected and handled by the system operators.

A short version of the results from the FMEA are reported in the table of Figure 9, while the long version can be found in the table of Figure 11 in the Appendix A. In the short version, only one of the various failure modes is analyzed for each of the 16 components identified.

Component Name	Component ID	Function	Failure Mode	Failure Cause	Failure Effect		Failure Detection	Failure Handling
					Local	Global		
Colour tanks	Tc	store the paint	leakage	broken sealing	uncontrolled emptying of the tank	paint loss & prevent the production of certain colour types	decreasing paint level while the valve is closed	stop the system and call maintenance team to repair the sealing
Mixing basin	B	store the mixed paint	overfilling	basin filling while already full	loss of paint	loss of paint	visual inspection & high paint level reached	flush the basin
Pump	xBP	drain the mixing basin	restricted flow	clogging	reduced paint flow	reduced paint flow	incoherent paint flow rate wrt. the pump's aperture	call the maintenance team to unclog the pump
Motors	xByM	mix the paints	fail to start	defective or broken	no mixing of the paints	bad quality paint	speed sensor records a rotational speed of 0 while the motor is on	stop the system and repair or subsitute the motors
Rotational speed sensors	xBS	measure the motors' rotational speed	loss of input	defective or broken	no more measures of motors' rotational speed	no more measures of motors' rotational speed	no more measures of motors' rotational speed displayed by the sensors	repair or substitute the sensors
Pneumatic valves	xTcV	drain the tanks	dysfunctional (fails to keep the aperture or to be opened or closed)	defective or broken	uncontrolled or blocked paint flow	may lead to a loss of paint or impedes the tanks emptying	incoherence between the actual and the theoretical paint levels	stop the system and repair or subsitute the valves
Flow meter sensors	xTc(B)F	measure the paint flow speed	erroneous indication	defective or broken	wrong measures of the paint flow speed	uncontrolled paint flow	incoherence between the actual and the theoretical paint levels	repair or substitute the sensors
pH sensors	xTcH	measure the paint's pH	loss of input	defective or broken	paint's actual pH unknown	paint's actual pH unknown	paint's pH not recorded by the sensors	repair or substitute the sensors
Temperature & humidity sensors	xTcT	measure the paint's temperature & humidity	erroneous indication	defective or broken	uncertain paint's temperature and humidity	affect the final paint's quality, or critical if undetected fire	incoherence with the measures recorded in the other tanks	repair or substitute the sensors asap
Retro-reflective level sensors	xTc(B)yL	checkpoint the paint levels	erroneous indication	defective or broken	wrong checkpoints of the paint's level	uncertain paint's level	incoherence with the measures from the pulsed radar level sensors	repair or substitute the sensors
Pulsed radar level sensors	xTcR	measure the exact paint levels	erroneous indication	defective or broken	wrong measures of the paint's level	uncertain paint's level	incoherence with the checkpoints from the retro-reflective level sensors	repair or substitute the sensors
Electronic vibration sensor	xE	indicate if the mixing station is active	loss of input	defective or broken	no indication of the mixing station's state of operation	no indication of the mixing station's state of operation	no indication of the mixing station's state of operation	repair or substitute the sensors
CPU of the PLCs	-	generate control signals based on the inputs	signal loss or inaccuracy	defective or broken	incorrect operation	global process mismatch	bad paint's quality + watchdog processor	maintenance or substitution
I/O module of the PLCs	-	interface between PLCs, sensors, and actuators	delayed operation	loss of communication	process delay	process delay	global process time delay	maintenance
SCADA laptop	-	manage the supervision of the mixing station	hard drive failure	mechanical wear	loss of data	loss of historical data	disk health software + watchdog processor	frequent data backups
Ethernet cables	-	shuttle data between devices	wear and tear	copper wiring degrades over time	performance worsening	performance worsening	data transfer at slower speeds, and buffering and lags take place	replace the cables

Figure 9: Failure mode and effect analysis (FMEA) - short version

5.2 FTA

As mentioned previously, the FTA is a top-down analysis. The idea is to select an identified critical failure mode and to descend to its origin (in a traditional mechanical or industrial complex, it corresponds to the component or device that is down and causing the failure).

In the context of the color mixing station, the bad paint's quality was set as the general problem to investigate. After analyzing step by step the main causes of this failure mode, 19 of them were ultimately identified. Once all of these potential issues have been pointed out, some predictive maintenance can be put in place accordingly, and if the operators encounter any problem with respect to the final paint's quality, they now have an exhaustive checklist that they can consult to understand what could be the corresponding cause.

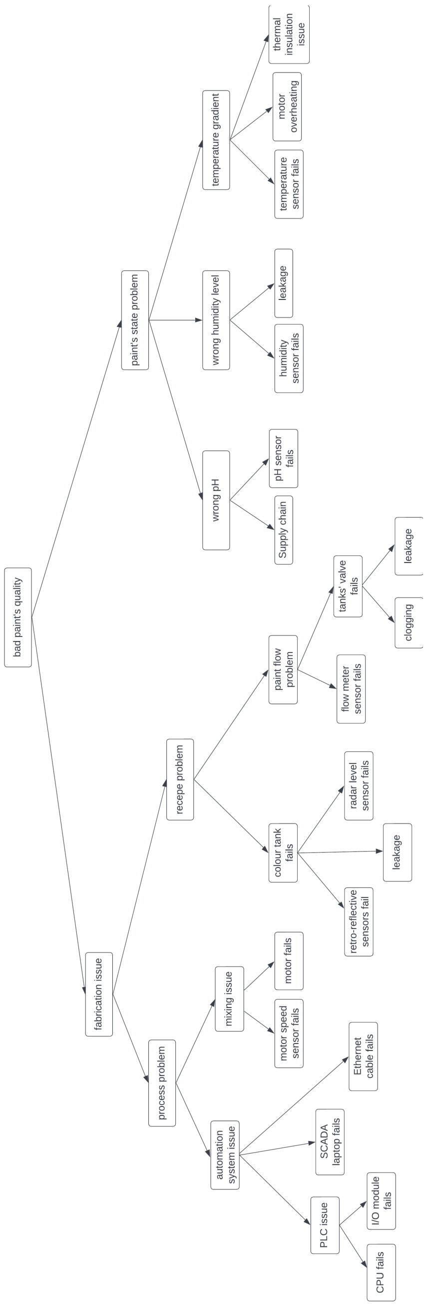

Figure 10: Fault tree analysis (FTA)

6 Conclusion

This report covers the design and implementation of the automation system of a paint mixing plant. It begins with detailing the selection and configuration of sensors and actuators, and then explains the integration of these components into the SCADA system. The hierarchical synoptic views developed for the SCADA system are presented, emphasizing their role in efficient monitoring and control by the system operators. The alarms and events are defined, and the implementation of event-driven and cyclic operations to ensure optimal performance without overloading communication links is explained. Additionally, qualitative dependability analyses through FMEA and FTA are conducted to identify potential failure modes and their impacts, which constitute the basis for predictive maintenance strategies. The system is designed with reliability and efficiency in mind, while incorporating provisions for future expansions as well.

7 Appendix A

Component Name	Component ID	Function	Failure Mode	Failure Cause	Failure Effect		Failure Detection	Failure Handling
					Local	Global		
Colour tanks	Tc	store the paint	leakage	broken sealing	uncontrolled emptying of the tank	paint loss & prevent the production of certain colour types	decreasing paint level while the valve is closed	stop the system and call maintenance team to repair the sealing
Colour tanks	Tc	store the paint	overfilling	tank filling while already full	loss of paint	loss of paint	visual inspection & very high paint level reached	flush the tank
Colour tanks	Tc	store the paint	complete emptying	too late refilling	empty tank	prevent the production of certain colour types	no paint flow detected while the valve is open	fill the tank
Mixing basin	B	store the mixed paint	leakage	broken sealing	uncontrolled emptying of the basin	loss of paint	decreasing paint level while the pump is closed or incoherence between actual and theoretical paint levels	stop the system and call maintenance team to repair the sealing
Mixing basin	B	store the mixed paint	overfilling	basin filling while already full	loss of paint	loss of paint	visual inspection & high paint level reached	flush the basin
Mixing basin	B	store the mixed paint	complete emptying	too late refilling	empty basin	no colour production	no paint flow detected while the pump is open	(fill and) flush the tanks
Pump	xBP	drain the mixing basin	dysfunctional (fails to keep the aperture or to be opened or closed)	defective or broken	uncontrolled or blocked paint flow	may lead to a loss of paint or impedes the basin emptying	incoherence between the actual and the theoretical paint levels	stop the system and repair or subsitute the pump
Pump	xBP	drain the mixing basin	restricted flow	clogging	reduced paint flow	reduced paint flow	incoherent paint flow rate wrt. the pump's aperture	call the maintenance team to unclog the pump
Pump	xBP	drain the mixing basin	leakage	crack formation	uncontrolled emptying of the basin	loss of paint	decreasing paint level while the pump is closed or incoherence between actual and theoretical paint levels	stop the system and repair or subsitute the pump
Motors	xByM	mix the paints	fail to start	defective or broken	no mixing of the paints	bad quality paint	speed sensor records a rotational speed of 0 while the motor is on	stop the system and repair or subsitute the motors
Motors	xByM	mix the paints	fail to stop	defective or broken	uncontrolled mixing of the paints	uncontrolled mixing of the paints	speed sensor records a non null rotational speed while the motor is off	unplug the motors from the power supply and repair them
Rotational speed sensors	xBS	measure the motors' rotational speed	erroneous indication	defective or broken	if the actual speed is too low, it may reduce the paint's quality	if the actual speed is too low, it may reduce the paint's quality	incoherence with the rotational speed set to the motors	repair or substitute the sensors
Rotational speed sensors	xBS	measure the motors' rotational speed	loss of input	defective or broken	no more measures of motors' rotational speed	no more measures of motors' rotational speed	no more measures of motors' rotational speed displayed by the sensors	repair or substitute the sensors
Pneumatic valves	xTcV	drain the tanks	dysfunctional (fails to keep the aperture or to be opened or closed)	defective or broken	uncontrolled or blocked paint flow	may lead to a loss of paint or impedes the tanks emptying	incoherence between the actual and the theoretical paint levels	stop the system and repair or subsitute the valves
Pneumatic valves	xTcV	drain the tanks	restricted flow	clogging	reduced paint flow	uncontrolled final colour type	incoherent paint flow rate wrt. the valves' aperture	call the maintenance team to unclog the valves
Pneumatic valves	xTcV	drain the tanks	leakage	crack formation	uncontrolled emptying of the tanks	loss of paint	decreasing paint level while the valves are closed or incoherence between actual and theoretical paint levels	stop the system and repair or subsitute the valves
Flow meter sensors	xTc(B)F	measure the paint flow speed	erroneous indication	defective or broken	wrong measures of the paint flow speed	uncontrolled paint flow	incoherence between the actual and the theoretical paint levels	repair or substitute the sensors
Flow meter sensors	xTc(B)F	measure the paint flow speed	loss of input	defective or broken	no measures of the paint flow speed	uncontrolled paint flow	no measures recorded while the valves or the pump are open	repair or substitute the sensors
pH sensors	xTcH	measure the paint's pH	erroneous indication	defective or broken	paint's actual pH unknown	paint's actual pH unknown	incoherence with paint's pH in other tanks	repair or substitute the sensors
pH sensors	xTcH	measure the paint's pH	loss of input	defective or broken	paint's actual pH unknown	paint's actual pH unknown	paint's pH not recorded by the sensors	repair or substitute the sensors
Temperature & humidity sensors	xTcT	measure the paint's temperature & humidity	erroneous indication	defective or broken	uncertain paint's temperature and humidity	affect the final paint's quality, or critical if undetected fire	incoherence with the measures recorded in the other tanks	repair or substitute the sensors asap
Temperature & humidity sensors	xTcT	measure the paint's temperature & humidity	loss of input	defective or broken	no measures of paint's temperature and humidity	affect the final paint's quality, or critical if undetected fire	no measures displayed	repair or substitute the sensors asap
Retro-reflective level sensors	xTc(B)yL	checkpoint the paint levels	erroneous indication	defective or broken	wrong checkpoints of the paint's level	uncertain paint's level	incoherence with the measures from the pulsed radar level sensors	repair or substitute the sensors
Retro-reflective level sensors	xTc(B)yL	checkpoint the paint levels	loss of input	defective or broken	no checkpoints of the paint's level	uncertain paint's level	no checkpoints displayed	repair or substitute the sensors
Pulsed radar level sensors	xTcR	measure the exact paint levels	erroneous indication	defective or broken	wrong measures of the paint's level	uncertain paint's level	incoherence with the checkpoints from the retro-reflective level sensors	repair or substitute the sensors
Pulsed radar level sensors	xTcR	measure the exact paint levels	loss of input	defective or broken	no measures of the paint's level	uncertain paint's level	no measures displayed	repair or substitute the sensors
Electronic vibration sensor	xE	indicate if the mixing station is active	erroneous indication	defective or broken	indicates that the station is off while it is active (or viceversa)	indicates that the station is off while it is active (or viceversa)	incoherence with the fact that the mixing station is working or not	repair or substitute the sensors
Electronic vibration sensor	xE	indicate if the mixing station is active	loss of input	defective or broken	no indication of the mixing station's state of operation	no indication of the mixing station's state of operation	no indication of the mixing station's state of operation	repair or substitute the sensors
CPU of the PLCs	-	generate control signals based on the inputs	inconsistent treatment	defective or broken	malfunction	system delay	wrong process duration	maintenance or substitution
CPU of the PLCs	-	generate control signals based on the inputs	overflow memory	PLC programming	incorrect operation	process mismatch	process overduration	maintenance
CPU of the PLCs	-	generate control signals based on the inputs	signal loss or inaccuracy	defective or broken	incorrect operation	global process mismatch	bad paint's quality + watchdog processor	maintenance or substitution
I/O module of the PLCs	-	interface between PLCs, sensors, and actuators	delayed operation	loss of communication	process delay	process delay	global process time delay	maintenance
I/O module of the PLCs	-	interface between PLCs, sensors, and actuators	loss of inputs	defective or broken	no I/O signals	automation system failure	unusual station operation	maintenance or substitution
SCADA laptop	-	manage the supervision of the mixing station	power failure	power outage	server shutdown	monitoring total failure	power monitoring system	equip the laptop with an uninterruptible power supply
SCADA laptop	-	manage the supervision of the mixing station	hard drive failure	mechanical wear	loss of data	loss of historical data	disk health software + watchdog processor	frequent data backups
SCADA laptop	-	manage the supervision of the mixing station	software crash	software defect	freezing	control failure	application error logs	restart the software
SCADA laptop	-	manage the supervision of the mixing station	network failure	network defect	communication loss	monitor / control failure	network monitoring + watchdog processor	troubleshoot the network
Ethernet cables	-	shuttle data between devices	physical damage	bent or pinched cables	signal strength reduction	signal strength reduction	visual inspection of the cables + data packets losses during transfers	replace the cables
Ethernet cables	-	shuttle data between devices	wear and tear	copper wiring degrades over time	performance worsening	performance worsening	data transfer at slower speeds, and buffering and lags take place	replace the cables
Ethernet cables	-	shuttle data between devices	installation issues	improper crimping or connection to wrong ports	prevents proper signal transmission	prevents proper signal transmission	unstable Ethernet connection that randomly drops devices from the network	properly insert cables into the correct cable ports and avoid bending or straining them

Figure 11: Failure mode and effect analysis (FMEA) - long version

List of Figures

List of Tables

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