Software Engineering for Autonomous Systems

AIR POLLUTION MONITORING AND CONTROL SYSTEM

Professor: Davide Di Ruscio

Students:

Ruocco Giulia – mat. 288597

Sciarra Davide – mat. 288650

Sicchio Giovanni – mat. 291326

University of Study of L'Aquila

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Summary

INTRODUCTION

Autonomous systems are devices or systems capable of operating independently, without the need for direct human control. These systems can be implemented in various contexts, such as autonomous vehicles, drones, industrial robots, and many other sectors. The key to autonomous systems is the ability to perceive the surrounding environment, make decisions, and adapt and/or modify their behavior without constant human intervention. This category of systems also includes proactive systems, i.e., systems capable of predicting the trend of environmental parameters and implementing adaptations before these parameters exceed defined thresholds.

Autonomous systems and their components are based on the MAPE-K cycle.

This document details the development project of a proactive autonomous system for air purification in an industrial environment. The system aims to monitor and manage levels of critical air pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), fine dust, and humidity (which affects fine dust concentration), in different sections of the industrial environment.

The system consists of sensors placed in each section of the plant, which constantly detect the levels of the aforementioned components. Simultaneously, actuators are used to remove the detected pollutants, ensuring a safe and healthy working environment.

The GOALS section will precisely outline the monitored components, the types of sensors used, and the actuators employed for pollutant management. In the **ADAPTATION GOALS** section, minimum and harmful limits will be defined for each of the monitored components. In case of exceeding harmful limits, the system is designed to immediately activate alarms, which in turn trigger the actuators at maximum power, ensuring rapid and effective interventions to reduce health risks for workers and industrial process efficiency.

All system functionalities are thoroughly described in the **FUNCTIONAL/NON-FUNCTIONAL REQUIREMENTS** section. In the **INTERVENTION LEVELS** paragraph, all system action modes will be presented, also considering the activation and deactivation of alarms in response to detected levels of air pollutants.

In the context of the **MAPE-K LOOP**, a detailed analysis of the implementation of the various components of the cycle (Monitoring, Analysis, Planning, Execution, and Knowledge) will be provided, while the implementation of the components will be elaborated in the **COMPONENTS IMPLEMENTATION** section.

For a better understanding of the system's operations and the results obtained, a series of graphical screens obtained through the use of **GRAFANA** will be presented.

The **CONCLUSIONS** and **INSTRUCTIONS** for executing the autonomous system locally will be reported in the last two sections of this document.

GOALS

It has been chosen to design an autonomous system capable of detecting and regulating the presence of pollutants in the air in industrial environments.

The sensors identified for the system are:

Air quality sensors:

The system utilizes a series of specific sensors to measure the presence of air pollutants. The sensors can be designed to detect substances such as: carbon monoxide (CO), carbon dioxide (CO_2), fine dust, and humidity.

- **Carbon Monoxide (CO) Detection Sensors**
  These sensors detect the presence of CO in the air, a colorless and odorless gas produced by incomplete combustion of carbon, often associated with vehicle traffic and gas appliances. Excessive exposure to this toxic gas can have serious effects on human health and is difficult to detect without specific instruments. The use of **ventilation systems/windows** allows the removal of this harmful substance.
- **Carbon Dioxide (CO_2) Detection Sensors**
  These sensors detect the presence of CO_2 in the air, a colorless, odorless, and tasteless gas. Prolonged exposures or high concentrations can be harmful and cause adverse health effects. These sensors are

important for assessing indoor air quality and are connected to **ventilation systems/windows** for disposal.

- **Fine Dust Detection Sensors**
  These sensors detect the presence of fine dust in the air, very small particles (often in the nanometer range) that are particularly harmful as they can penetrate deep into human lungs causing respiratory problems, cancer, and effects on the nervous system. These sensors come in two types: **laser diffusion and ultrasound**. Laser diffusion sensors project a beam and measure the concentration based on the amount of light reflected by the particles. Ultrasound sensors measure changes in sound velocity caused by the presence of particles in the air. **Humidification/Nebulization systems** help reduce the concentration of solid particles in the air.
- **Relative Humidity Sensors**
  Humidity is also a parameter that needs constant monitoring as it is directly linked to the amount of fine dust in the air. Increased humidity leads to a decrease in solid particles of fine dust, but excessive humidity in the air can cause damage to human health as well as a humidity level below a certain threshold. The sensors used are devices designed to measure the humidity content in the air. Through a **humidification system**, the amount of water vapor in the air is regulated (increased/decreased).

Actuators:

- **Ventilation System**
  Mechanical and/or natural systems capable of extracting stale air from within a closed environment and replacing it with fresh air from the outside. Mechanical systems refer to **suction and ventilation systems** or **automatic windows**, while natural ventilation refers to the use of **windows and openings.**
- **Humidification/Nebulization System**
  Systems capable of reducing dust in the air. Humidity can promote the aggregation of particles, making it easier for them to be captured by particulate filters.
- **Alarm**
  Devices capable of alerting personnel inside the factory/industry in case the levels of carbon monoxide, carbon dioxide, fine dust, or humidity are well beyond the safety threshold. This way, the area can be evacuated. There is an alarm for each monitored parameter and a general alarm for the industry section.

ADAPTATION GOALS

GOALS	DESCRIPTION	EVALUATION METRIC
Maintain the quantity of **carbon monoxide (CO)** below harmful levels.	The concentration of carbon monoxide must remain below the harmful threshold.	Limit: **$CO < 40$ mg/m^3** Danger limit: **$CO < 100$ mg/m^3**
Maintain the quantity of **carbon dioxide (CO_2)** below harmful levels.	The concentration of carbon dioxide must remain below the harmful threshold.	Limit: **$CO_2 < 1000$ ppm** Danger limit: **$CO_2 < 5000$ ppm**
Maintain the quantity of **fine dust matter (PM)** below harmful levels.	The concentration of fine dust must remain below the harmful threshold.	Limit: **$PM < 25$ µg/m^3** Danger limit: **$PM < 50$ µg/m^3**
Maintain the **humidity level (%RH)** within the limits of harmful values.	The humidity concentration must between the harmful lower limit and the harmful upper limit.	**$30 < \%RH < 50$**

Alert the personnel through the **alarm** when the parameters exceed the harmful safety limits	It is important to alert the personnel within the environment for safety preservation.	**$CO < 100$ mg/m³** **$CO_2 < 5000$ ppm** **PM < 50 µg/m³**

FUNCTIONAL REQUIREMENTS

Requirement F1

Type: Functional - Monitoring

Description: The system monitors the presence of carbon monoxide in the air and sends the data to Knowledge.

Priority: High

Requirement F2

Type: Functional - Monitoring

Description: The system monitors the presence of carbon dioxide in the air and sends the data to Knowledge.

Priority: Medium

Requirement F3

Type: Functional - Monitoring

Description: The system monitors the presence of fine dust and sends the data to Knowledge.

Priority: High

Requirement F4

Type: Functional - Monitoring

Description: The system monitors the amount of humidity in the environment and sends the data to Knowledge.

Priority: Medium

Requirement F5

Type: Functional - Analysis

Description: The system analyzes data stored in the Knowledge related to levels of carbon monoxide, carbon dioxide, fine dust, and humidity in the environment.

Priority: High

Requirement F6

Type: Functional – Planning

Description: The system proactively plans an adaptation strategy to keep monitored parameters within safe thresholds.

Priority: High

Requirement F7

Type: Functional - Execution

Description: The system communicates with the actuators to put into practice what is planned by the Planner.

Priority: High

Requirement F8

Type: Functional - Alarm

Description: The system alarms staff if the levels of monitored substances are such that they could cause damage to their health.

Priority: High

NON-FUNCTIONAL REQUIREMENTS

Requirement NF1

Type: Non-Functional - Data

Description: The system persistently maintains monitoring and alarm utilization data (general section alarm and individual section parameter alarms) through an Influx DB database.

Priority: High

Requirement NF2

Type: Non-Functional - Data

Description: The system accesses Knowledge so that it can analyze the data and provide an efficient proactive adaptation strategy.

Priority: High

Requirement NF3

Type: Non-Functional - Data

Description: The system can store new sensors and actuators.

Priority: Medium

Requirement NF4

Type: Non-Functional - Reusability

Description: The system can be adapted and used in environments different from the one covered in the project by exploiting a network of different sensors and actuators.

Priority: Medium

TECHNOLOGIES USED

The software has been entirely implemented using the Python programming language and the following technologies:

- **Message Broker: MQTT**

MQTT, which stands for Message Queuing Telemetry Transport, is a lightweight and scalable messaging protocol. We used the MQTT protocol to obtain data from sensors and enable communication between some of the components of the MAPE-K cycle. This data was sent through Python on the dedicated topic and subsequently processed by other components.

Our **topics** are:

- **industry**: topic within which data obtained through sensors are published. Specifically, the topic is defined by:
  - **industry:** fixed part indicating the main topic;
  - **sectionName:** name of the section with which the values are associated;
  - **parameter:** parameter whose values are published. The possible parameters are **CO, CO_2,** **fineDust** and **Humidity**.

  Example topic: **industry/Section_a/fineDust**

- **status**: topic within which data obtained after analysis of parameter values are published. Specifically, the topic is defined by:
  - **status:** fixed part indicating the main topic;
  - **sectionName:** name of the section with which the values are associate.

  Example topic: **status/Section_a/**

- **plans**: topic within which the adaptation plans for each section are posted. Specifically, the topic is defined by:
  - **plans:** fixed part indicating the main topic;
  - **sectionName:** name of the section with which the values are associate.

  Example topic: **plans/Section_a/**

- **executions**: topic within which messages about actions to be performed by actuators are posted. Specifically, the topic is defined by:
  - **executions:** fixed part indicating the main topic;
  - **sectionName:** name of the section with which the values are associated.

  Example topic: **executions/Section_a/**

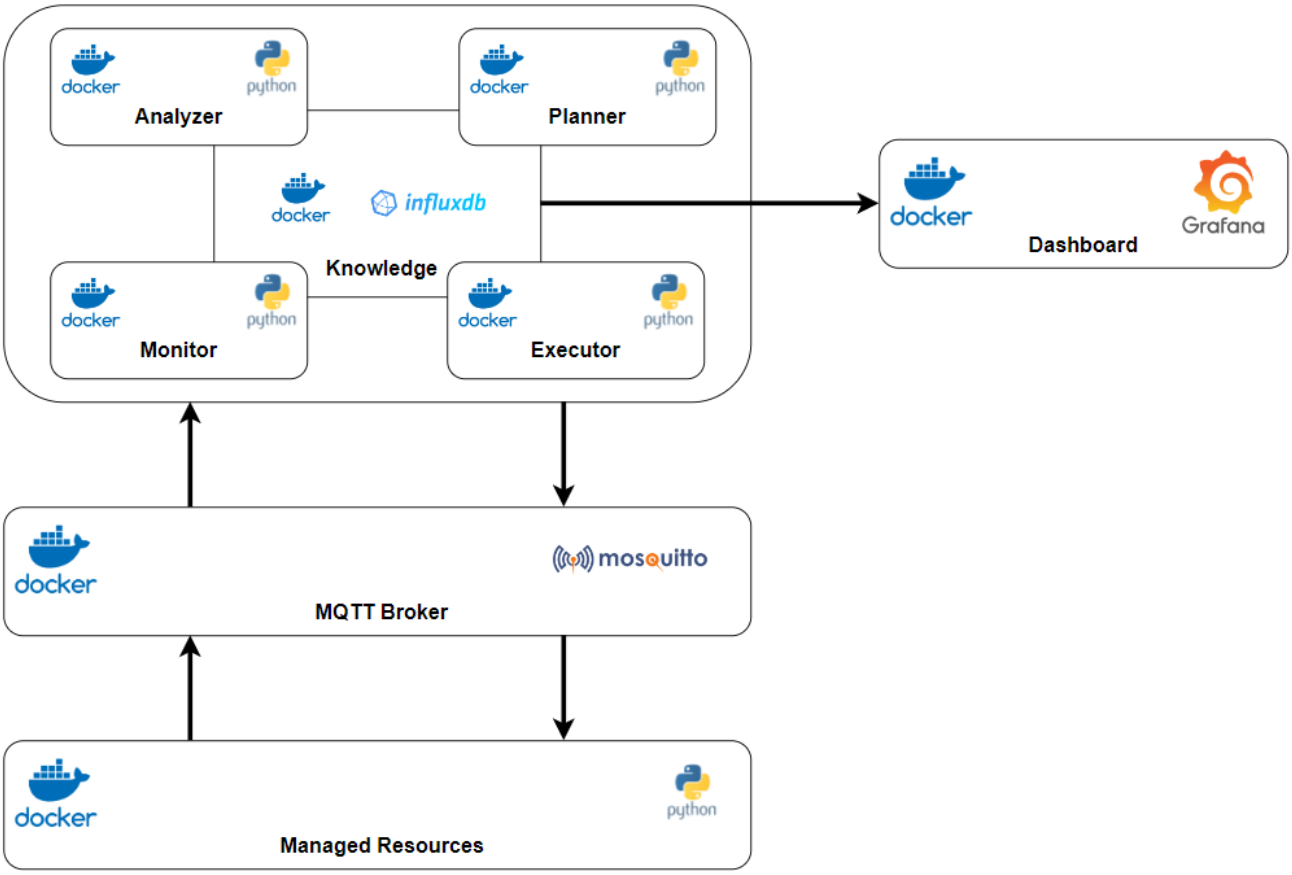
- **Database: InfluxDB**

This database was chosen for its ability to handle large volumes of data from environmental sensors and other data sources. InfluxDB proved to be reliable and flexible, allowing efficient data analysis and management within our project, with the advantage of easy reads and writes using Python files.

- **Grafana (Dashboard)**

Grafana is used primarily as a graphical user interface and was therefore used to visualize and understand the data. The main advantage of Grafana that we found is that, in addition to providing better visualization, it provides a way to create multiple dashboards simultaneously and allowed us to better manage information.

SYSTEM ARCHITECTURE



LEVELS OF INTERVENTION

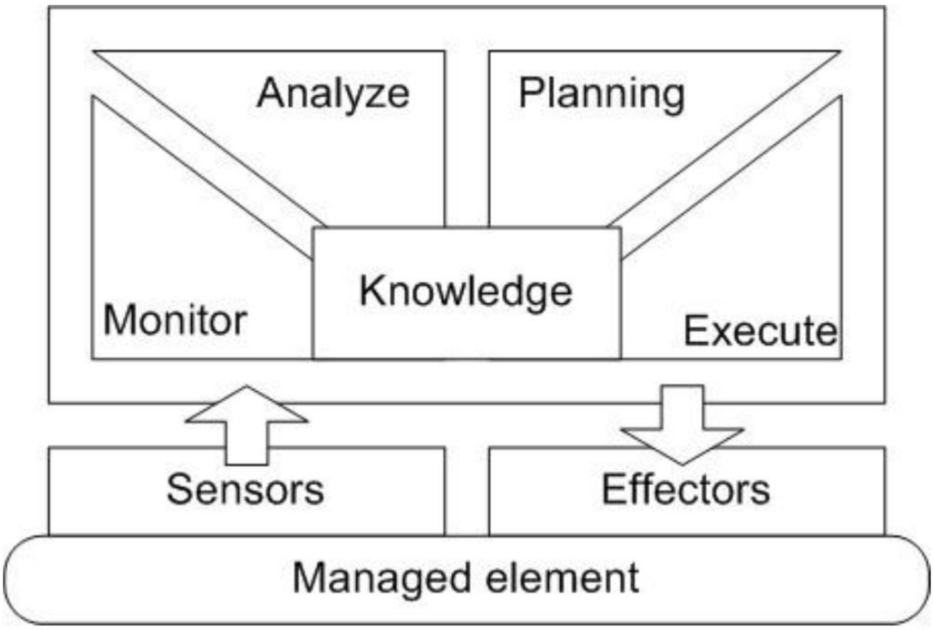
To ensure a healthy environment for occupants, the system operates on three distinct intervention levels based on the detected levels of air pollutants such as CO, CO_2, fine dust, and humidity. Each intervention level is designed to anticipate, prevent or resolve critical situations, ensuring that air quality remains consistently within safe limits. Below, we will explore in detail the three intervention levels of our air purification system and their operation in different situations.

1. **Basic Level:**
   In this state, when CO, CO_2, fine dust, and humidity levels are all within safe limits. The system continues to monitor the status of the parameters without enabling the actuators.

2. **Early Alarm Level:**
   The system predicts that pollutant values may exceed safe limits in the short term, activates the actuators at a lower power to bring the parameters back within safe limits, thus preventing a critical state from being reached.

3. **Alarm Level:**
   When the system detects that pollutant levels have already exceeded **harmful limits** or predicts that they will do so quickly, it activates the actuators at full power and sounds an alarm to alert staff of the critical situation. The actuators operate at full power to quickly reduce pollutant levels and return the air to a safe condition.

MAPE-K LOOP IMPLEMENTATION



Our system is based on the Mape-K Loop, using a container system to ensure clear separation between each element of the loop. Components are deployed on separate containers, which are managed through the use of Docker, and which communicate through the use of a Message Broker and Knowledge. The components that describe the data flow are:

- **MONITOR**: Component responsible for collecting data obtained from sensors (CO_2, CO, humidity, and fine dust) and writing these values into the knowledge.

- **KNOWLEDGE**: Component responsible for storing collected data realtive to the measured parameters, alarm status (general and specific for each parameter), and safety limits for each parameter.

- **ANALYZER**: Component whose role is to retrieve parameter data from Knowledge, predict a trend by exploiting the past values, and compare the predictions with the threshold limits (also retrieved from Knowledge). Then the determined symptoms are communicated to the Planner through specific messages (one for each symptom) using the MQTT Message Broker.

- **PLANNER**: Component responsible for formulating adaptation strategies, making decisions and implementing policies necessary to bring the value of parameters back within safe thresholds. The strategy is defined based on the symptoms calculated by the Analyzer and published in the relevant topic. Through the MQTT broker, this component, retrieves the symptoms and then publishes the defined adaptation plans.

- **EXECUTOR**: This component based on what is decided and planned works to execute the plan through the use of actuators. Through the use of the MQTT broker, actuators are activated or deactivated.

COMPONENTS IMPLEMENTATION

MONITOR:

This component enables monitoring of the industrial environment, interacting with the InfluxDB database and the MQTT broker to receive and manage data from sensors.

When the monitor connects to the MQTT broker, it makes a subscription to the topic **industry** to receive data about the parameters and alarms of each section. When it receives a message, it analyzes it and stores it in the database.

With this implementation, the monitor ensures continuous tracking of events in the industrial environment, enabling alarm management and data collection for analysis.

ANALYZER:

This component is designed to analyze data from sensors in an industrial environment.

First, it connects to an InfluxDB database to receive data and to an MQTT broker to send it. Next, the section names and parameters of the industrial environment are retrieved via database calls. This information is crucial to properly perform queries to retrieve values.

Next, data on parameter measurements and their safety limits are retrieved from the database for each section.

Below, a linear regression algorithm is run to predict the next two values, for each parameter in each section, based on the values obtained through the sensors over a time frame. For testing purposes, this time frame is set to 2 minutes and allows for the retrieval of approximately the last 60 measurements.

Finally, checks are performed to determine whether the second of the expected values is within the safety ranges. Based on what is analyzed a status is associated with each parameter:

- **0**: parameter is within the safe range or has returned low after a dangerous state;
- **1**: parameter exceeds the upper limit;
- **2**: parameter exceeds the danger upper limit;
- **3**: parameter is less than the minimum value.

The resulting status is then published using the MQTT protocol in the main topic **status**.

Full topic: **status/Section_Name/**

At the end of the check phase, an additional check is made on the general alarms of the individual sections. If even one of these alarms is active, then the "sampling" time is reduced. If, on the other hand, all alarms are turned off, then the "sampling" time remains the standard one.

PLANNER:

This component is responsible for retrieving system symptoms (determined by the analyzer) and defining action plans to bring the parameters back within safe ranges.

The component connects to the Message Broker and subscribes to topic **status** and, for each message received, determines an **action plan** based on the content of the message.

For each section, based on the symptoms, a string is defined containing the plans for the individual parameters, specifically there is a correspondence between symptom and plan:

- **Symptom: 0 – Plan: No Actions**
- **Symptom: 1 – Plan: Decrease**
- **Symptom: 2 – Plan: Danger**
- **Symptom: 3 – Plan: Increase**

The resulting strings are subsequently posted in the main topic **plans**.

Full topic: **plans/Section_Name/**

EXECUTOR:

This component is responsible for retrieving the plans defined by the Planner and executing them by correctly operating the actuators based on what was retrieved.

This component also connects to the MQTT Broker and subscribes to the topic in which execution plans are posted: **plans**. Each message received is analyzed and, based on the content, actuators are activated by publishing messages on a dedicated topic.

The incoming message consists of four parts (one for each parameter) and is related to a single section. Since, CO and CO_2 parameters refer to the same actuators as well as Fine Dust and Humidity, it was chosen to analyze together the plans relating first to one pair and then to the other.

Also in this component, a two-part string is defined, each representing the execution defined for each parameter pair.

Regarding the CO and CO_2 parameters, the following cases were identified based on the first two parts of the content of the incoming message:

- **Case "no_actions" for both:** no action required for CO and CO_2, the ventilation system is then turned off and the windows closed. Message: OFF
- **Case "danger" only for CO:** dangerous situation for CO only, the windows are opened fully and there is activation of ventilation to maximum power with attached activation of the parameter alarm and the general alarm of the section. Message: DANGER-CO
- **Case "danger" only for CO_2:** dangerous situation for CO_2 only, involves opening the windows, activating the ventilation to full power, and activating the parameter alarm and general section alarm. Message: DANGER- CO_2
- **Case "danger" for both:** dangerous situation for both parameters, the windows are opened, there is activation of ventilation at maximum power and activation of the general alarm and alarms of the two parameters. Message: DANGER-ALL
- **Otherwise:** Situation where one and both parameters exceed the "base" limit but not the danger limit, this results in the ventilation system being activated and the windows being partially opened. Message: ON

For the parameters **Fine Dust** and **Humidity** instead:

- **Case "no_actions" for both:** no action required for fine dust and humidity, there is turning off the humidification system. Message: OFF
- **Case "decrease" humidity and “no_actions” fine dust:** request to decrease air humidity, this implies the activation of the medium power air dehumidification system. Message: DEHUMIDIFY
- **Case "decrease" fine dust and “no_actions” humidity or "increase" humidity and “no_actions” fine dust:** Request for increased air humidity due to amount of fine dust or low humidity percentage in the air. Medium power humidification system is activated. Message: HUMIDIFY

- **Case "danger" only for humidity:** dangerous situation only for humidity, therefore, you need air dehumidification at maximum power and activation of general alarm and for the parameter. Message: DANGER-D
- **Case "danger" only for fine dust:** hazardous situation only for fine dust, humidification of air at maximum power and subsequent activation of general alarm and parameter is required. Message: DANGER-H
- **Case "danger" for both:** dangerous situation for both fine dust and humidity, humidification of the air at maximum power and activation of the general alarm and for both parameters is implemented. Humidification of the air was chosen to give priority to the disposal of fine dust as it is more harmful to human health. Message: DANGER-ALL

The resulting strings are then posted in the main topic **executions**.

Full topic: **executions/Section_Name/**

MANAGED RESOURCES:

The Managed Resources section of our project includes a set of elements that are crucial for controlling the industrial environment. These resources include the various sections of the plant (Section A, Section B, Section C), which represent the different working environments within the industry. In addition, we operate the automatic windows and the ventilation system, which is designed to efficiently expel carbon monoxide (CO) and carbon dioxide (CO_2) from the environment.

To keep pollutant and humidity levels under control, we have implemented a humidification/dehumidification system. This system not only regulates the humidity in the air, but also helps control the concentration of fine dust, ensuring a safe and healthy working environment.

Finally, alarm management is a key aspect of managed resources. In the event that harmful limits are exceeded for any of the monitored parameters, a general section alarm is triggered that promptly signals the danger, allowing actuators to be activated at maximum power for rapid expulsion of pollutants, and, in addition, data is maintained on which parameter caused the danger.

Section:

Section provides a complete abstraction of a section within an industry, including: sensors, data simulation, actuator control based on sensed environmental conditions, and alarm system for the section and individual parameters.

The actuators present for each section are: **Windows, VentilationSystem, HumidificationSystem, and Alarm**. Each of these actuators is made to use MQTT to retrieve the messages on the topic **executions**, so as to gesture their operation based on the content of the messages.

Simulations of sensor data within the section are performed. Then, the simulated values are published, via MQTT, to the topic **industry**, enabling the system to receive and use this data.

Alarms:

Alarms are triggered when the system communicates the need for an activation by specifying the type of hazard being encountered and thus which alarm should be called in.

Several cases may occur, depending on the communication that has arrived, the general alarm and parameter-specific alarms are activated. They can be activated:

- Carbon monoxide (CO) alarm.
- Carbon dioxide (CO_2) alarm.
- Both alarms for CO and CO_2.
- Alarm for humidity.
- Alarm for fine dust.
- Both alarms for fine dust and humidity.

In the event that a hazard is resolved or overcome and therefore the alarm is no longer needed, it is deactivated for the respective parameter. In case all alarms are deactivated, the general alarm of the section will also be deactivated.

Humidification Systems:

The humidification system is able to increase or decrease the humidity in the air based on what is posted on the topic to which it is subscribed.

Based on the content of the post, the corresponding action suitable for the case is chosen:

- **Increase humidity:** Moisture in the section of interest is increased according to the specified power.
- **Decrease humidity:** In the opposite way to the previous one, the humidity in the corresponding section is lowered with a specified power.
- **Keep the humidity constant:** Constant humidity in the corresponding section is maintained by deactivating the humification system.

Ventilation Systems:

The ventilation system for a given section allows ventilation to be turned on or off based on what is received via MQTT and adjusts ventilation power according to environmental conditions.

Based on the content of the message, one of the following actions is performed:

- If the message indicates that the system is activated, medium power ventilation is activated accordingly.
- If the message indicates a CO or CO_2 related hazard, ventilation is always activated but at a higher power to address the hazardous situation.
- If the message indicates the ventilation is turned off then it is turned off.

Windows:

The opening and closing of windows in a given section is also handled through messages retrieved from the Broker, allowing the status of windows to be controlled based on what is received.

- If the message indicates windows are opened then windows are opened partially, consequently reducing CO and CO_2 levels.
- If the message indicates a dangerous situation, the windows are opened fully.
- If the message indicates the windows are closed then they are simply closed.

CONFIGURATION:

Component made simply to write the **Safety Limits** data to the database..

GRAFANA

On Grafana, we created charts and tables with data related to the industrial environment. We defined a dashboard for each section, each having:

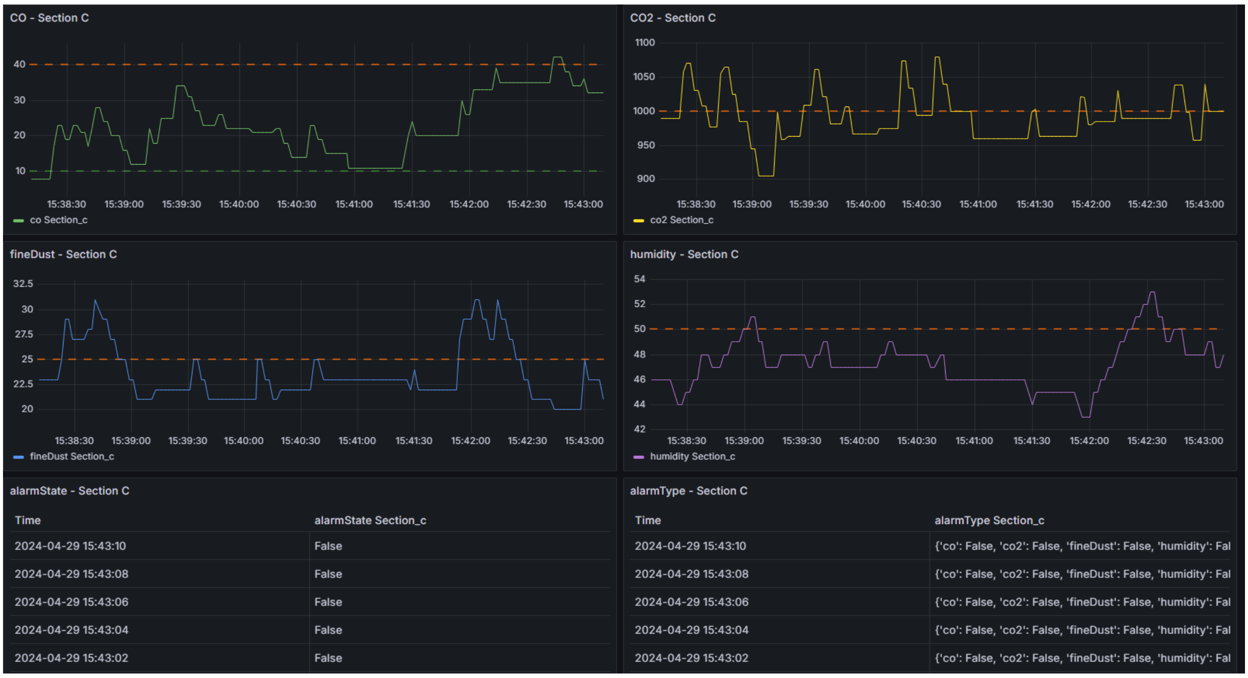
- Four graphs: one for each section parameter;
- Two tables: one for general section alarm and one for parameter-specific alarms.

Below are some screenshots related to the dashboards

- ## SECTION A

- ## SECTION B

- ## SECTION C



CONCLUSIONS

The system we have built meets all the necessary requirements for the creation of an autonomous system for the control and disposal of air pollutants within an industrial setting.

The system is able to make decisions autonomously and plan adaptation plans to keep parameters within safe ranges and, if necessary, alarm staff if these values exceed the safe limit.

Our system can efficiently predict parameter trends (by predicting the next two values) by exploiting past measurements, thus allowing us to categorize the system as proactive.

In conclusion, possible future developments may include the use of more accurate mechanisms to predict parameter value trends.

INSTRUCTIONS

Prerequisites: having Docker installed.

Run on your prompt the command: **git clone https://github.com/sicchio99/SE4AS.git**

- Enter the directory cmd and run the command: **docker compose build**
- Execute the command: **docker compose up**

In order to view dashboards on Grafana:

- Open Grafana through the link: http://localhost:3000
- Log in by entering as username and password: **admin.**
- Go to the Dashboards section and select the section of interest.