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MASTER

In **Electrical and Electronic Engineering**

Option: **Control**

Title:

Design of a Smart PLC-Based Fire Safety System using Fuzzy Logic

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Abstract

This project aims to develop a smart fire detection and fire-fighting system to enhance fire safety measures of a three fire zone industrial facility. An intelligent fire detection algorithm based on fuzzy logic is proposed, integrating four sensor inputs (smoke obscuration rate, temperature, flame radiance and carbon monoxide concentration) for accurate fire identification and classification. Additionally, a PLC-based automation of the fire-fighting pumping system of each fire zone is developed aiming to optimize fire suppression resource deployment. The integration of these intelligent systems is achieved via a SCADA system, enabling real-time monitoring, control, and decision support. The fire detection algorithm was implemented using the MATLAB software and rigorously tested with simulations performed with the industry-standard NIST Fire Dynamics Simulator yielding highly promising results which demonstrated and validated the detection algorithm's effectiveness and robust performance. These application results demonstrate the potential of intelligent fire detection to significantly improve fire safety, minimize damage, and protect lives through accurate, rapid response times, and optimized resource allocation.

Dedication

I dedicate this modest work to my beloved parents, family and friends and everyone who supported me throughout the way. May Allah, the Almighty, preserve them all.

Acknowledgment

First and foremost, I would like to praise Allah the Almighty, the Most Gracious, and the Most Merciful for bestowing His countless blessings upon me throughout my academic journey and enabling me to complete this thesis successfully.

I would like to express my sincere gratitude and profound appreciation to my esteemed supervisor, Dr. Radhia KACED, for her invaluable guidance, unwavering support, and continuous encouragement. Her expertise, dedication, and insightful feedback have been essential in shaping this work and enriching my research experience.

No acknowledgement would be complete without expressing my heartfelt thanks to my beloved parents, whose unconditional love, sacrifices, and constant prayers have been the driving force behind my achievements. Their unwavering faith in me has been a source of strength and motivation throughout this arduous endeavor. May Allah preserve them.

I would also like to extend my sincere appreciation to my classmates for their camaraderie and support during our academic journey.

We would conclude with our deepest gratitude to all those who have directly or indirectly contributed to the successful completion of this thesis, whether through their expertise, guidance, or moral support.

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List of Acronyms

API: Application Programming Interface
CFD: Computational Fluid Dynamics
CO: Carbon Monoxide
CPU: Central Processing Unit
DB: Data Block
FB: Function Block
FBD: Function Block Diagram
FC: Function
FDS: Fire Dynamics Simulator
FIS: Fuzzy Inference System
HMI: Human-Machine Interface
iDB: Instance Data Block
IDE: Integrated Development Environment
IEC: International Electrotechnical Commission
IL: Instruction List
LAD: Ladder Diagram
MF: Membership Function
MIMO: Multiple Input and Multiple Output
MISO: Multiple Input and Single Output
NFPA: National Fire Protection Association
NIST: National Institute of Standards and Technology
OB: Organization Block
OEMs: Original Equipment Manufacturers
PLC: Programmable Logic Controller
PRV: Pressure Relief Valve
RTU: Remote Terminal Unit
SCADA: Supervisory Control and Data Acquisition
SCL: Structured Control Language
SFC: Sequential Function Chart
SMV: Smoke View
ST: Structured Text
TIA: Totally Integrated Automation

General Introduction

Fire safety is a critical concern across various industries, from large-scale manufacturing facilities to residential and commercial buildings. The devastating consequences of fire incidents, including loss of life, property damage, and environmental impact, underscore the importance of robust fire detection and suppression systems. The motivation behind this project stems from the need for intelligent and adaptive fire safety systems that can effectively detect and respond to fire incidents. Traditional fire safety systems often rely on fixed threshold values for individual parameters or predefined rules. However, fire events can exhibit complex patterns involving multiple interrelated variables, making it challenging to achieve accurate and robust detection using traditional methods which can be susceptible to false alarms or delayed responses in evolving and dynamic fire scenarios.

This master project thesis presents the design and development of a smart PLC-based fire safety system that leverages the flexibility of fuzzy logic for enhanced fire detection and response capabilities. The proposed system integrates advanced automation and supervision solutions with a sophisticated fire detection algorithm, enabling accurate and adaptive fire detection and suppression strategies. To achieve the most accurate fire detection possible, the fuzzy inference system (FIS) combines multiple input parameters, which are: temperature, smoke obscuration rate, flame radiance, and carbon monoxide concentration. The central hypothesis of this project is that the integration of fuzzy logic techniques with PLC-based automation can significantly improve fire detection accuracy and enable efficient and automated fire-fighting operations, ultimately enhancing overall fire safety.

The primary objectives of this project are to:

- To design and implement a PLC-based fire safety system capable of accurate fire detection using a fuzzy logic approach.
- To develop a robust automation solution for fire-fighting equipment, including pumps, valves, and sprinkler systems, controlled by the PLC.
- To integrate a Supervisory Control and Data Acquisition (SCADA) system for monitoring and visualization of the fire safety system's operation.
- To assess the performance of the fuzzy logic-based fire detection algorithm using simulated fire scenarios and compare it with other methods.

The thesis is structured into four chapters, each addressing a specific aspect of the fire safety system design and implementation:

Chapter 1, "Theoretical Foundation & Project Tools," establishes the fundamental knowledge required for understanding the system such as the National Fire Protection Association (NFPA) standards, fuzzy logic theory and the various tools employed throughout the project.

Chapter 2, "System Description," provides an overview of the entire system along with a detailed breakdown of the fire-fighting system. It outlines the fire-fighting equipment and pumps deployed across three distinct fire zones: the Administrative Zone, Industrial Zone, and Sea Zone.

Chapter 3, "Automation & Supervision Solution," focuses on the system automation and supervision solution developed for the fire-fighting system. This section covers the selection and configuration of the PLC and explains the sequential logic of the automation program illustrated with flowcharts. Additionally, it showcases the SCADA system.

Chapter 4, "Fire Detection Algorithm," delves into the core innovation of this project – the fire detection algorithm based on Fuzzy Logic. It explains the rationale behind employing Fuzzy Logic for this application. The chapter showcases the FIS designed for fire detection, along with its inputs, rule base and output. This chapter also explores the integration of the FIS into the TIA Portal environment using the MATLAB PLC Coder toolbox. Finally, the fire detection algorithm undergoes a validation process to analyze its performance utilizing the Fire Dynamics Simulator (FDS) to simulate real-life fire scenarios.

In the **Conclusion,** the key takeaways and contributions of this project are highlighted with the inclusion of a discussion on potential future work and developments.

- CHAPTER I -

Theoretical Foundation

&

Project Tools

I.1. Introduction:

This chapter establishes the theoretical foundation and introduces the key tools utilized in this project. It covers fire theory, including the fire triangle, fire classes, and extinguishment methods. Additionally, it discusses relevant NFPA standards for fire protection systems, focusing on pumping systems and fire mesh design. The chapter also explores fuzzy logic theory, encompassing fuzzy sets, membership functions, and inference systems, which underpins the development of intelligent fire detection algorithms. Finally, it provides an overview of the project tools, including automation tools like PLCs, SCADA systems, and programming languages, as well as fire detection algorithm tools such as MATLAB and Fire Dynamics Simulator.

I.2. Fire Theory:

I.2.1. Definition:

Fire is the rapid oxidation of a material, a chemical process known as combustion which releases heat, light, and byproducts. This oxidation reaction involves the chemical combination of oxygen with other substances. The speed of this reaction determines the intensity of the fire.

There are three main theories explaining fire: the fire triangle, the tetrahedron of fire, and the life cycle of fire. The fire triangle, the oldest and most basic, states that three elements are necessary for fire: fuel, oxygen (or an oxidizer), and heat (or energy). These elements are analogous to the sides of a triangle, and fire cannot exist unless all three are present. [1]

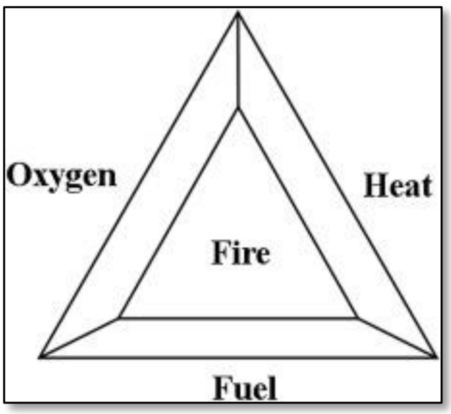


Figure I.1: *Fire Triangle*

- Fuel can be any substance that burns, categorized into various classes including elements (like carbon, sulfur, and phosphorus), hydrocarbons, carbohydrates (like wood and paper), covalently bonded gases (like carbon monoxide), and other organic compounds.
- Oxygen acts as the oxidizer, typically found in ambient air.
- Heat is the energy source that initiates and sustains the combustion process. It can be generated chemically, mechanically, electrically, or by nuclear methods. Heat transfer to the fuel occurs through conduction, convection, and radiation.

The fire triangle emphasizes that removing any one of these elements will extinguish the fire. This principle is essential for firefighting.

I.2.2. Fire Classes:

Fires are categorized based on the fuel involved, determining the most effective extinguishing agent. The NFPA (National Fire Protection Association) system, used in the United States, classifies fires based on their fuel type, allowing firefighters to select appropriate extinguishing agents and avoid unwanted side effects.

Fire Class	**Fuel/Heat Source**
Class A	Ordinary combustibles
Class B	Flammable liquids and gases
Class C	Electrical equipment
Class D	Combustible metals
Class K	Cooking oil or fat

Table I.1: *Fire Classes*

I.2.3. Fire Extinguishment:

Fire is an exothermic reaction, meaning it releases heat. This heat feedback sustains the fire. To extinguish fire, we need to interrupt this heat feedback by cooling the fuel below its ignition temperature.

Water is the most common extinguishing agent, utilizing its latent heat of vaporization and specific heat to absorb heat energy. However, water has drawbacks, including its conductivity, low viscosity, high surface tension, and reactivity with certain materials.

For materials that react with water, alternative methods are employed, such as removing the oxygen supply, effectively removing the oxidizer leg from the fire triangle. In this approach, foam is used as the primary extinguishing agent or as a secondary one mixed with water.

I.2.4. Fire Fighting:

Firefighting involves extinguishing destructive fires. Firefighting systems can be automatically or manually actuated, and often include components like:

- **Fire alarm control panel:** Monitors the system and relays information.
- **Primary Power supply:** Provides energy to the system.
- **Secondary (backup) Power supplies:** Provides energy in case of power failure.
- **Initiating Devices:** Act as inputs to the fire alarm control unit, triggered manually or automatically.
- **Notification appliances:** Alert individuals about the fire, prompting evacuation.
- **Fire sprinkler system:** Discharges water upon fire detection.
- **Safety interfaces:** Control various aspects of the building to mitigate fire spread and facilitate evacuation.

Effective firefighting relies on a well-designed system that meets safety standards and ensures the safety of firefighters and occupants.

I.3. NFPA Standards:

The National Fire Protection Association (NFPA) is a global non-profit organization dedicated to eliminating fire and other hazards. They develop, publish, and advocate for a wide range of standards that address fire safety, electrical safety, building construction, and other related areas. These standards are widely adopted by governments, industries, and individuals to ensure safety and minimize risks. NFPA standards provide a consistent framework for safety practices across different jurisdictions and industries. They are developed by experts and represent the best available knowledge and practices for fire and life safety. Many NFPA standards are incorporated into building codes and regulations, making compliance essential. By following NFPA standards, organizations and individuals can significantly reduce the risk of fire, explosions, and other hazards. There are 400+ standards. However, only few of them are relevant to this project's application. [2] Here is a short overview of the main NFPA standards:

- **NFPA 1 - Fire Code:** This comprehensive standard sets the minimum requirements for fire prevention, protection, and life safety in buildings and structures. It covers topics like fire alarm systems, fire extinguishers, sprinkler systems, building construction, and emergency procedures.
- **NFPA 101 - Life Safety Code:** This standard focuses on life safety in buildings and addresses issues like emergency exits, fire alarm systems, fire suppression systems, and accessibility. It is widely adopted for a range of buildings, including hospitals, schools, and commercial structures.
- **NFPA 25 - Standard for the Inspection, Testing, and Maintenance of Water-based Fire Protection Systems:** This standard is a general maintenance guide that ensures the effectiveness and reliability of water-based fire protection systems. It covers the inspection, testing, and maintenance of a wide range of water-based fire protection systems, including: water tanks, fire pumps, sprinkler systems, standpipe systems and fire hydrants.
- **NFPA 720 - Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment:** This standard outlines specific requirements for the installation of CO detectors in residential, commercial, and industrial settings. This includes the location of the CO detectors, their type as well as the required number to be used depending on the layout of the building.

- **NFPA 72 - National Fire Alarm and Signaling Code:** This standard sets the requirements for fire alarm systems, including design, installation, testing, and maintenance. It covers topics like system components, notification appliances, and communication systems.

I.3.1. Pumping System Minimum Requirements:

According to the NFPA 1–Fire Code Standard, The fire-fighting system must include the following components:

- A water reserve
- A pumping system
- Piping system
- Fire hydrants and/or sprinklers
- Piping accessories and tapping connections
- Block valves

I.3.1.1. The Pumping System:

The purpose of the pumping system is to automatically supply pressurized water to a fire-fighting system. This water serves as the primary extinguishing agent, utilized in various forms like sprinklers, water curtains, and fire hydrants, maximizing heat absorption and fire suppression. All these systems require a constant supply of pressurized water from a dedicated network. In the event of a fire, the demand for water is triggered either manually by opening a fire hydrant or automatically through the activation of sprinklers. The pumping equipment responds by starting the main pump, ensuring the necessary flow and pressure to meet the firefighting needs.

I.3.1.2. Pumping Unit Design:

The pumping unit itself must be strategically located near the water source. It must house all the equipment needed to pump water to the fire water network. It must contain all the electrical equipment and accessories required for automatic and manual control of the fire pumps. Subsequently, emergency power must be readily available to guarantee uninterrupted operation during a fire.

To ensure reliable fire protection, the system has to incorporate two separate pumping units, each powered by a different energy source: electricity and diesel. This redundancy guarantees a continuous water supply even in the event of a power outage. Each pump is designed to independently meet the full water flow and pressure requirements of the facility, providing a robust safety net in case of fire. Ideally, a fire water system should be equipped with three main pumps: two electrically powered, with one acting as a standby, and one diesel-powered pump. This configuration provides maximum redundancy and reliability. However, if a three-pump system is not feasible, a minimum of two pumps is mandatory: one electric and one diesel. This ensures a continuous water supply even in the event of a power outage.

The fire water network must incorporate two auxiliary pumps know as Jockey pumps. They are small, electrically powered units that operate in an alternation by automatically starting and stopping as needed. Their primary function is to compensate for any pressure losses that may occur due to leaks or other factors thus maintaining constant pressure within the pumping system.

I.3.1.3. Fire Mesh Design:

A fire mesh is a critical design element in the fire water network, ensuring system integrity even in the event of a failure. This means that every point in the network has at least two separate and independent water supply routes. If one supply route becomes unavailable, the other remains active, preventing system failure. A simple valve operation can isolate the damaged section, allowing maintenance without compromising the overall fire protection. This looped piping network is clearly identified by its distinctive red paint.

The extent of the fire water network must encompass the entire area needing protection. This is achieved through a strategic placement of fire hydrants by ensuring that the area is completely covered, leaving no gaps or "shadow" zones. To maintain optimal pressure and accessibility, the minimum distance between two hydrants is 50 meters. Additionally, fire hydrants must be positioned at least 10 meters away from building facades. Finally, for balanced pressure distribution, it's ideal to position hydrants in a way that creates equidistant meshes within the network.

Pressure and flow are two essential parameters in fire suppression, whether using water, foam or both. While theoretical calculations for these values are guided by regulations based on the specific risks being protected, practical implementation is equally important. To achieve optimal pressure and flow, several factors must be continuously monitored:

- Water Reserve Volume
- Pumping System Efficiency
- System Sealing (preventing leaks)

I.4. Fuzzy Logic Theory:

Fuzzy logic is a type of logic that goes beyond the strict "true" or "false" of traditional logic. It allows for degrees of truth, represented by numbers between 0 and 1, making it ideal for handling vague and uncertain information. This is particularly useful in real-world situations where decisions often involve imprecise or subjective factors. Fuzzy logic can represent statements that are completely true or false, and it can also represent those that are partially true and/or partially false. It mimics how humans make decisions based on imprecise information. It provides a mathematical framework for representing and manipulating this vagueness. [3]

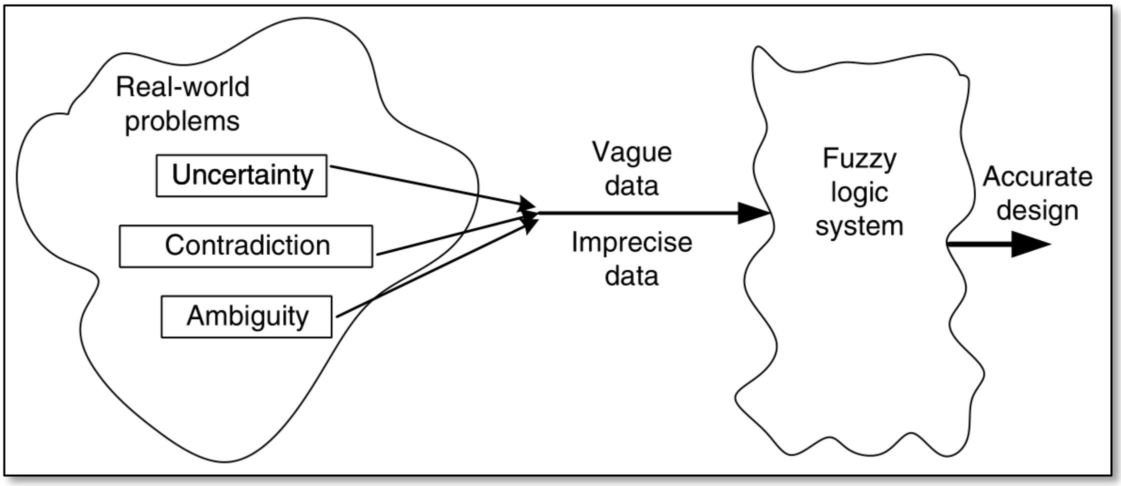


Figure I.2: *Fuzzy Logic General Idea*

The core of fuzzy logic involves mapping input values to output values using a set of "if-then" rules. These rules are evaluated simultaneously, and their order doesn't matter. The rules themselves are built around variables and the descriptive terms (like "hot" or "cold") that define those variables. Before applying fuzzy logic, the range of values and the meaning of the descriptive terms for each variable have to be defined. For example, "hot" water and the temperature range it encompasses have to be determined.

I.4.1. Fuzzy Sets:

Let X be a space of points (objects), with a generic element of X denoted by x. Thus, X = {z}. A fuzzy set (class) A in X is characterized by a membership (characteristic) function $f_A(x)$ which associates with each point in X a real number in the interval [0, 1], with the value of $f_A(x)$ at x representing the "grade of membership" of x in A. In other words, a fuzzy subset A of X is the set of all ordered pairs, (x, $f_A(x)$), such that x is an element of X, and the value of element $f_A(x)$ indicates the degree of membership of the element x in the subset A. Thus, the nearer the value of $f_A(x)$ to unity, the higher the grade of membership of x in A.

I.4.2. Membership Functions:

A membership function (MF) is curve that defines how each point in an input set of possible values (called the universe of discourse) is mapped to a degree of membership (membership value). This degree of membership is represented by a number between 0 and 1. Let us now discuss the most common and most relevant membership functions.

I.4.2.1. Triangular Function:

A triangular membership function is defined by three parameters {a,b,c} as depicted by the equation below:

$$f_{trimf}(x;a,b,c) = \left\{\begin{matrix} 0, & x \leq a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b \leq x \leq c \\ 0, & c \leq x \end{matrix}\right\} \ldots\textbf{(I.1)}$$

Or, more concisely as:

$$f_{trimf}(x;a,b,c) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \ldots\textbf{(I.2)}$$

As an example, let {a,b,c} = {3,6,8}, the resulting curve is illustrated in the figure I.3 below.

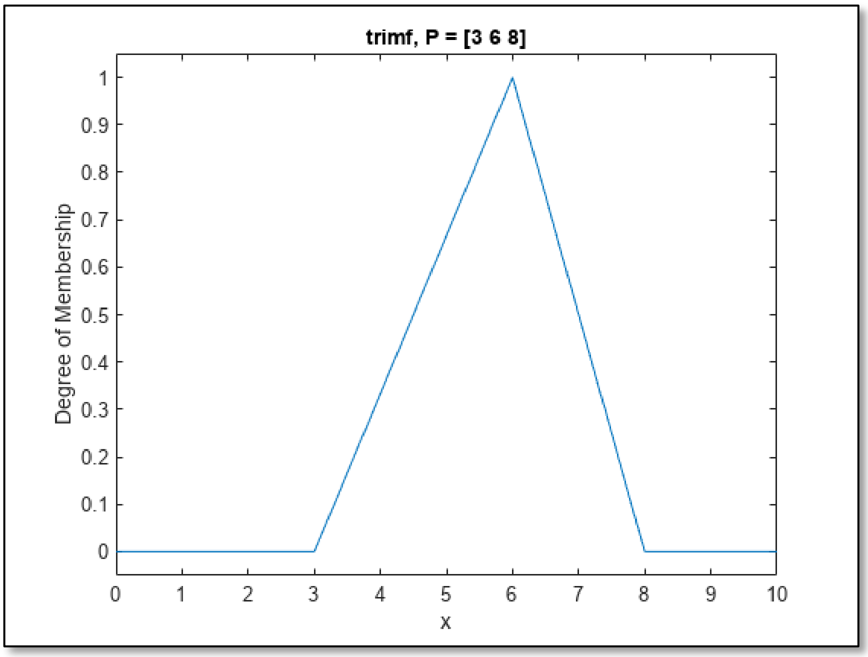


Figure I.3: *Triangular Membership Function Example*

I.4.2.2. Trapezoidal Function:

A trapezoidal membership function is defined by four parameters {a,b,c,d} as depicted by the equation below:

$$f_{trapmf}(\mathrm{x}; \mathrm{a}, \mathrm{b}, \mathrm{c}, \mathrm{d}) = \begin{cases} 0,\ x < a. \\ \frac{x-a}{b-a},\ a \le x \le b. \\ 1, b \le x \le c. \\ \frac{d-x}{d-c}, c \le x \le d. \\ 0, d \le x. \end{cases} \quad \textbf{...(I.3)}$$

Or, more concisely as:

$$f_{trapmf}(x; a, b, c) = \max\left(\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right) \textbf{...(I.4)}$$

As an example, let {a,b,c,d} = {1,5,7,8}, the resulting curve is illustrated in the figure I.4 below.

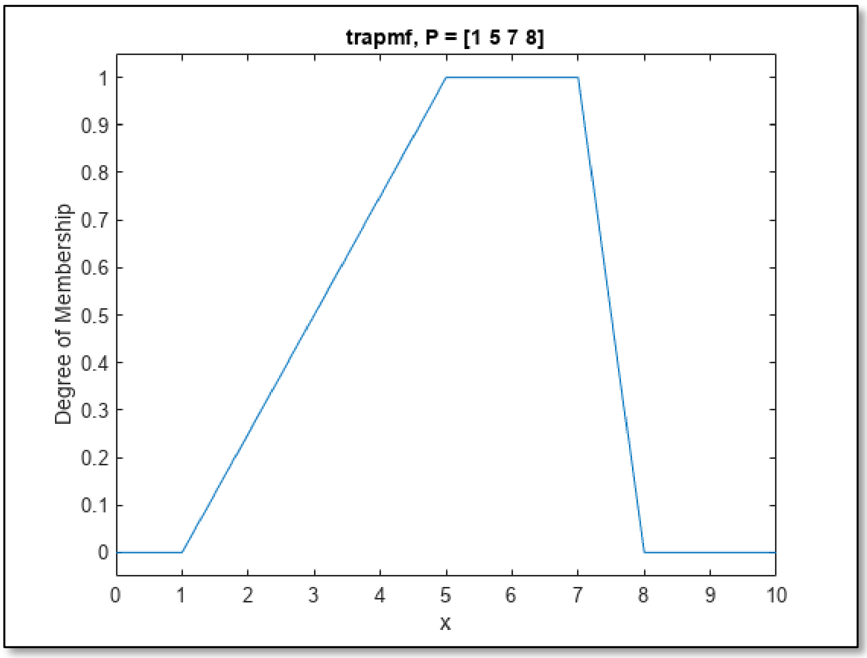


Figure I.4: *Trapezoidal Membership Function Example*

I.4.2.3. Linear Z-shaped Saturation Function:

This function is defined by two parameters {a,b} as depicted by the equation below:

When $< b$:

$$f_{linzmf}(x; a, b) = \left\{ \begin{matrix} 1, & x < a \\ \frac{a-x}{a-b}, & a \leq x \leq b \\ 0, & x > b \end{matrix} \right\} \ldots \textbf{(I.5)}$$

When $= b$:

$$f_{linzmf}(x; a, b) = \left\{ \begin{matrix} 1, & x < a \\ 0, & x \geq a \end{matrix} \right\} \ldots \textbf{(I.6)}$$

As an example, let {a,b} = {4,6}, the resulting curve is illustrated in the figure I.5 below.

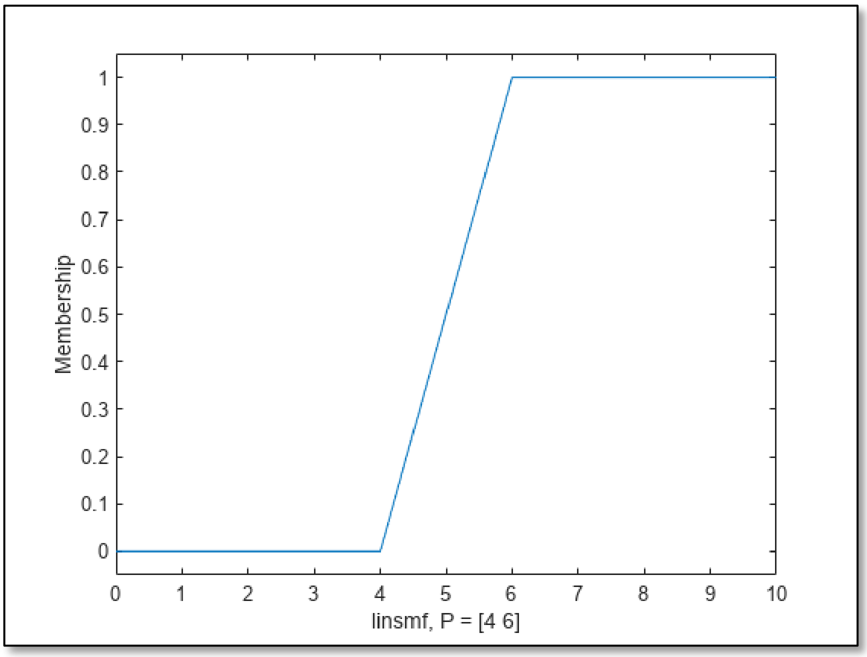


Figure I.5: *Linear Z-shaped Saturation Membership Function Example*

I.4.2.4. Linear S-shaped Saturation Function:

This function is also defined by two parameters {a,b} as depicted by the equation below:

When $< b$:

$$f_{linsmf}(x;a,b) = \begin{Bmatrix} 0, & x < a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & x > b \end{Bmatrix} \text{...(I.7)}$$

When $= b$:

$$f_{linsmf}(x;a,b) = \begin{Bmatrix} 0, & x < a \\ 1, & x \geq a \end{Bmatrix} \text{...(I.8)}$$

As an example, let {a,b} = {4,6}, the resulting curve is illustrated in the figure I.6 below.

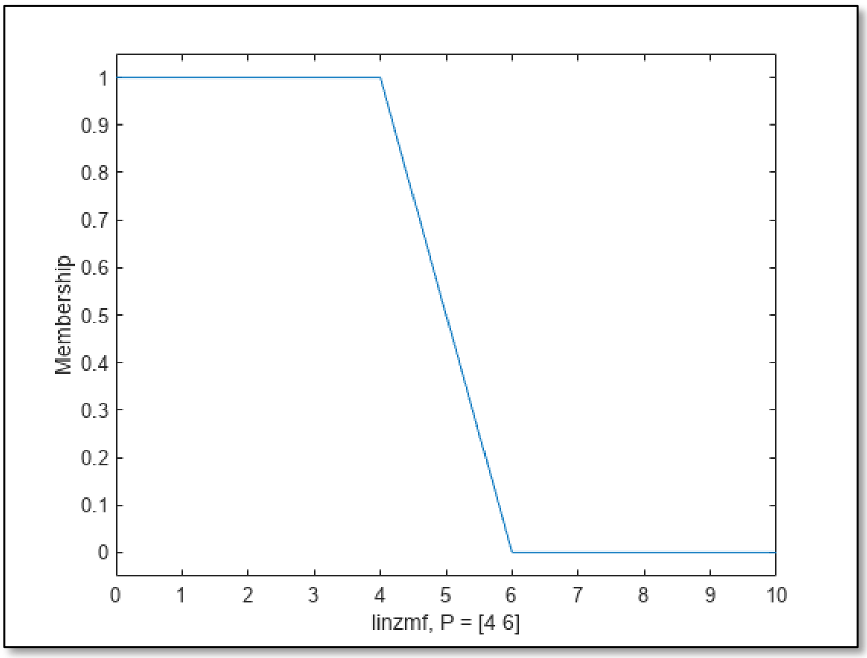


Figure I.6: *Linear S-shaped Saturation Membership Function Example*

I.4.3. Fuzzy Set Operations:

Fuzzy set operations, unlike crisp set operations, deal with the degrees of membership of elements in fuzzy sets. These operations are used to combine and manipulate fuzzy sets, allowing for more nuanced and flexible reasoning than traditional set theory. Assuming A and B are two fuzzy sets with degree of membership $\mu_A$and μ_B respectively for an input u. Let us define basic fuzzy set operations.

I.4.3.1. Intersection (AND):

The intersection of two fuzzy sets A and B, denoted as A ∩ B, is a fuzzy set where the membership of an element in the intersection is the minimum of its membership in A and B.

$$\mu_{A\cap B}(u) = \min\{\mu_A(u), \mu_B(u)\}\text{...}\textbf{(I.9)}$$

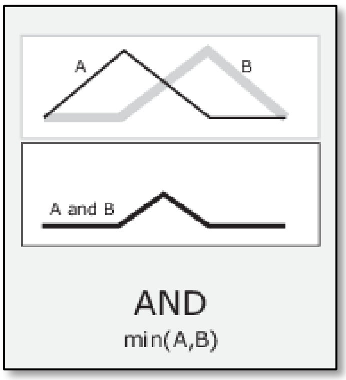


Figure I.7 : *Intersection Fuzzy Operation*

I.4.3.2. Union (OR):

The union of two fuzzy sets A and B, denoted as A ∪ B, is a fuzzy set where the membership of an element in the union is the maximum of its membership in A and B.

$$\mu_{A\cup B}(u) = \max\{\mu_A(u), \mu_B(u)\} \ldots \textbf{(I.10)}$$

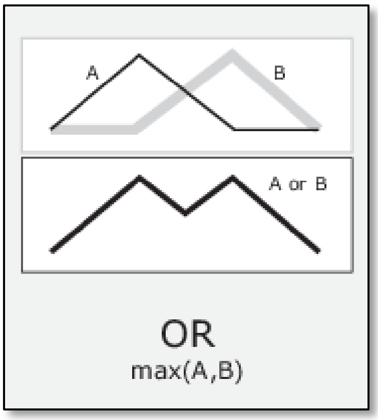


Figure I.8: *Union Fuzzy Operation*

I.4.3.3. Complement (NOT):

The complement of a fuzzy sets A, denoted as $\bar{A}$, is a fuzzy set where the membership of an element is the inverse of its membership A.

$$\mu_{\bar{A}}(u) = 1 - \mu_A(u) \ldots \textbf{(I.11)}$$

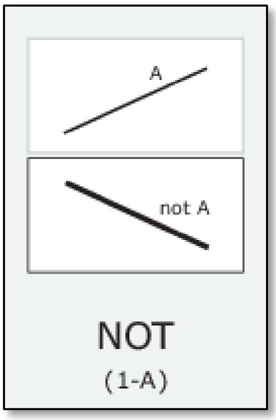


Figure I.9: *Complement Fuzzy Operation*

I.4.4. Fuzzy Logic Process:

The figure I.10 below provides an overview on the fuzzy logic workflow divided into three main steps: fuzzification, inference engine and defuzzification.

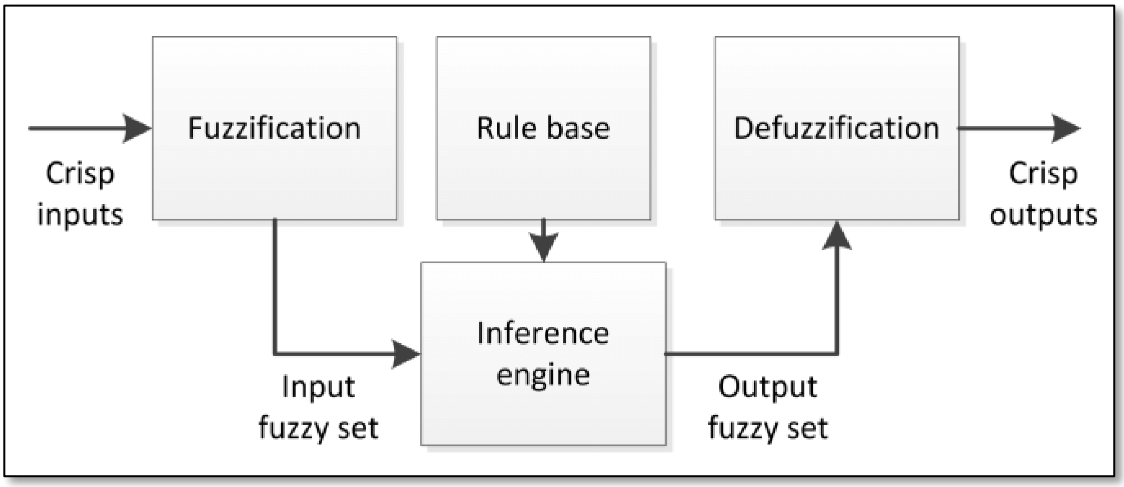


Figure I.10: *Fuzzy Logic Process Overview* [4]

I.4.4.1. Fuzzification:

Fuzzification is the process of converting crisp (precise) input values into fuzzy sets. This conversion takes the crisp input value and determines its membership in each fuzzy set based on the corresponding membership function. As defined in the above sections, each fuzzy set is associated with a membership function, which defines the degree of membership for each possible input value.

I.4.4.2. Inference Engine:

The fuzzy inference engine and rule base are the core of a fuzzy logic system, responsible for making decisions based on fuzzy inputs. The rule base is a collection of fuzzy rules that expressed in the form of "IF condition THEN consequence," where both the condition and consequence are fuzzy sets. The inference engine is the subsystem that interprets the fuzzy rules and derives outputs based on the fuzzy input values. This process is called “rule evaluation”. It then combines the results of multiple rule evaluations to produce a single fuzzy output.

I.4.4.3. Defuzzification:

Defuzzification is the final step in a fuzzy logic system, where the fuzzy output generated by the inference engine is converted back into a crisp (non-fuzzy) value that can be used to control a real-world system. There exists several defuzzification methods, but the centroid method is the most relevant to this application. It is applied by calculating the center of gravity of the fuzzy output set according to the following formula:

$$x_{centroid} = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)} \quad \text{...(I.12)}$$

Where:

- $x_{centroid}$ is the output (crisp) value
- $\mu(x_i)$ is the membership value of x_i in the fuzzy output set

I.4.5. Types of Fuzzy Inference Systems:

There are several types of FIS, each with its own strengths and weaknesses, catering to different application needs. Only type-1 fuzzy inference systems will be discussed in this section.

I.4.5.1. Mamdani FIS:

This is the most common and widely used type of FIS. It employs fuzzy sets for both the antecedent (condition) and consequent (action) parts of the fuzzy rules.

I.4.5.2. Sugeno FIS:

This type of FIS uses fuzzy sets for the antecedent (condition) but employs a crisp function for the consequent (action) part of the fuzzy rules.

Mamdani FIS	Sugeno FIS
Output membership function is present	No output membership function
The output of surface is discontinuous	The output of surface is continuous
Distribution of output	Non distribution of output (only Mathematical combination of the output and the rules strength)
Crisp result is obtained through defuzzification of rules	No defuzzification (crisp result is obtained using weighted average of the rules)
Less flexibility in the system design	More flexibility in the system design
More accuracy	Less accuracy
Used for MISO and MIMO systems	Used only for MISO systems
Well suited for human input	Well suited for mathematical analysis

Table I.2: *Comparison Chart between Mamadani and Sugeno FIS*

I.5. Project Tools:

I.5.1. Automation Tools:

I.5.1.1. Programmable Logic Controller (PLC):

A Programmable Logic Controller (PLC) is a robust, computer-based unit designed for controlling discrete or continuous processes in industrial environments. Originally developed as a replacement for relay systems in the automotive industry, PLCs have become widely spread across virtually every industry. PLCs are manufactured and sold worldwide by major control equipment manufacturers, as well as specialized companies catering to original equipment manufacturers (OEMs). PLC vendors provide extensive support, including application notes, technical articles, training courses, and comprehensive programming manuals. Familiarity with one PLC brand generally facilitates learning other brands. [5]

PLCs have gained widespread popularity due to their numerous advantages:

- **Cost-effectiveness:** PLCs are cost-effective for controlling complex systems compared to other controllers.
- **Flexibility:** PLCs are easily reconfigured to control different systems.
- **Sophisticated Control:** PLCs offer computational capabilities for more advanced control.
- **Troubleshooting Aids:** PLCs provide tools for simplifying programming and reducing downtime.
- **Reliability:** PLCs are built with reliable components, ensuring years of operation.

	Relays	**Solid-State Controls**	**Microprocessor**	**Minicomputer**	**PLCs**
Hardware cost	Low	Equal	Low	High	High to low (depending on number of controls)
Versatility	Low	Low	High	High	High
Usability	High	High	Low	Low	High
Troubleshooting & Maintainability	Yes	No	No	No	Yes
Computer-compatible	No	No	Yes	Yes	Yes
Arithmetic Capability	Low	Low	High	High	High
Information Gathering	No	No	Yes	Yes	Yes
Industrial Environment	Yes	No	No	No	Yes
Programming Cost	High (Wirin g)	High (Wiring)	Very High	High	Low
Reusability	No	No	Yes	Yes	Yes
Space required	Largest	Large	Small	Ok	Small

Table I.3: *Comparison between conventional Relay Systems, Solid-State control system, Microprocessor, Minicomputer and Programmable Logic Controller*

PLC Architecture:

While PLC configurations vary, they share common components and concepts:

- **Power Supply:** This can be integrated within the PLC or be an external unit. Common voltage levels include 24Vdc, 120Vac, and 220Vac.
- **CPU (Central Processing Unit):** This unit stores and processes the logic program.
- **I/O (Input/Output):** Input/output terminals allow the PLC to monitor processes and initiate actions.
- **Indicator Lights:** These lights indicate the PLC's status, including power on, program running, and faults, aiding in troubleshooting.

The following block diagram illustrates PLC's key components:

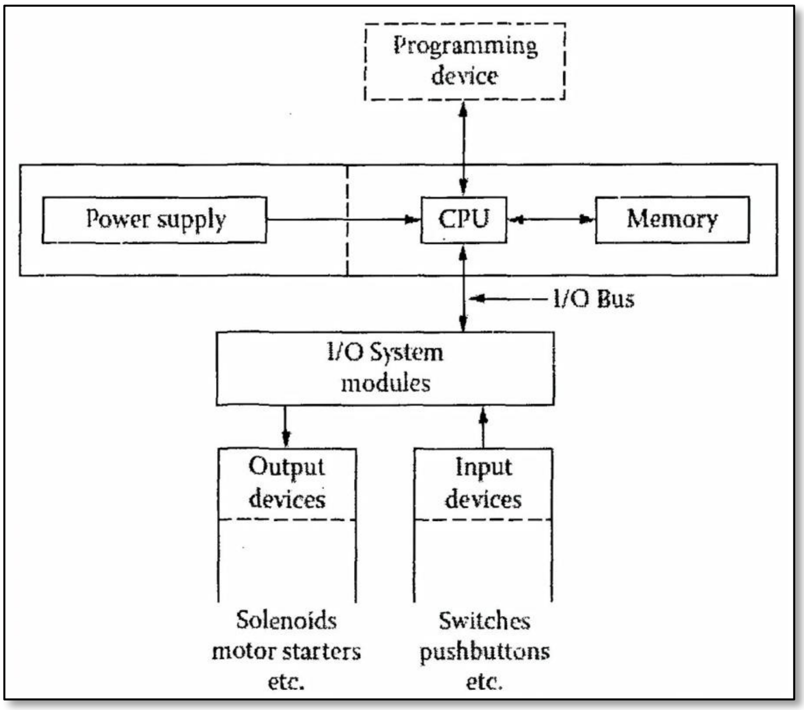


Figure I.11: *PLC's Architecture Block Diagram*

- **CPU:** Houses the microprocessor, memory modules, and communication circuitry for operation and communication with I/O and peripherals. The CPU makes decisions and controls the connected equipment.
- **Memory:** comes in 2 types: program memory and work memory. The program memory stores the program steps, typically in non-volatile memory (e.g., battery-backed CMOS or ROM) to prevent data loss during power outages. While the work memory stores auxiliary relay states, timer/counter values, I/O states, and arithmetic

logic calculation results. This area is often partially battery-backed to prevent data loss.

- **Power Supply Unit:** The PLC's internal power supply provides a DC supply to internal logic and microprocessor circuitry. It may also provide battery backup for auxiliary relay contacts, timer/counter values, and program memory (if using volatile RAM). The power supply is designed for the PLC's internal components, not for powering sensors and actuators, which require separate, isolated power sources.
- **Programming Device:** A programming device is needed to enter, modify, and troubleshoot the PLC program. It can be disconnected once the program is running but is used for monitoring the program while it's active. Programming devices come in three types: dedicated desktop programmer, handheld programmer and computer programmers.
- **Inputs and Outputs:** PLCs use inputs and outputs to monitor and control processes. Both can be categorized as logical (on/off) or continuous (varying values). Most PLC applications utilize logical inputs and outputs for simplicity and certainty. Smaller PLCs typically have built-in I/O, while larger PLCs use modules with 8 or 16 inputs of the same type. I/O modules are designed for both analog and digital inputs and outputs, accommodating different voltage and current ranges.
  - Outputs from PLCs typically control actuators, causing actions in the process. Common actuators include: solenoid valves, lights, motor starters and servo motors. Outputs can be relays, transistors, or triacs, depending on the application. Continuous outputs require special output modules with digital-to-analog converters.
  - Inputs come from sensors that convert physical phenomena into electrical signals. Common sensors include: switches, proximity switches, potentiometer and temperature sensors. PLC inputs can be AC, DC, sourcing, or sinking. Sourcing and sinking refer to the output method, dictating whether the device supplies power (sourcing) or simply switches current on/off (sinking).

PLC Programming:

PLC manufacturers provide their own programming editors. There are five common programming languages: Instruction List (IL), Structured Text (ST), Ladder Diagrams (LD), Function Block Diagram (FBD), and Sequential Function Chart (SFC). Ladder Diagrams (LD) are the most widely used language in industrial applications.

I.5.1.2. TIA Portal:

SIEMENS TIA Portal (Totally Integrated Automation Portal) is an all-in-one software suite that serves as a central platform for engineering, configuring, and commissioning PLC-based automation systems from SIEMENS. It provides a unified environment for various automation tasks, streamlining the development process and improving efficiency. This software includes:

- **Device Configuration:** Configuring and parameterizing hardware components like PLCs, drives, and I/O modules.
- **Program Development:** Creating and debugging PLC programs using languages like LAD, FBD, SCL, and Graph.
- **HMI Design:** Designing and configuring user interfaces for human-machine interaction.
- **Motion Control:** Programming and configuring motion control systems.
- **Process Automation:** Configuring and managing process automation systems.
- **Communication and networking:** TIA Portal facilitates seamless communication and networking by supporting a wide range of industrial protocols, such as PROFINET and PROFIBUS. This enables different devices and systems, including those from SIEMENS and other manufacturers, to interface smoothly.
- **Integrated Simulation and Testing:** The software offers built-in simulation tool called PLC-SIM which is used for testing and debugging automation programs without requiring a physical PLC. This accelerates development and reduces commissioning time.

PLC Programming:

TIA Portal offers several programming languages that can be used to write a PLC program. The most note-worthy of them are: Ladder Diagram (LAD), Function Block Diagram (FBD), Sequential Function Chart (SFC) and Structured Control Language (SCL). The focus will now be upon the languages of concern to this project's application.

Ladder Diagram (LAD):

Ladder Diagram (LAD) is a graphical programming language commonly used in industrial automation. It resembles a ladder with interconnected rungs, each representing a specific control logic step. LAD's foundation lies in relay logic, making it easy for electricians and technicians to grasp and troubleshoot. LAD programming employs symbols and graphical elements like contacts, coils, timers, and counters to represent electrical components and logical operations. These elements are connected in a way that mimics the behavior of relays and switches, creating the desired control logic. LAD is utilized in this project's application as the main PLC programming language

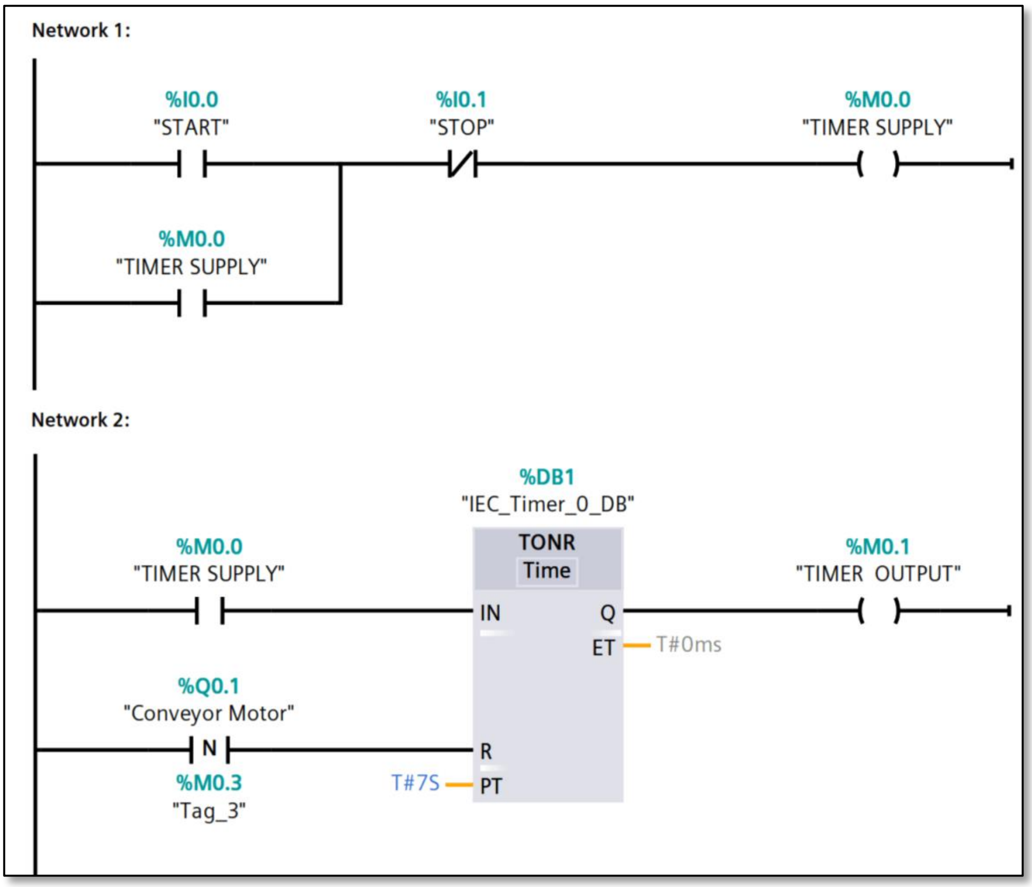


***Figure I.12:** Ladder Diagram PLC Programming Example*

Structured Control Language (SCL):

SCL (Structured Control Language) is a high-level programming language based on Pascal, designed for structured programming in industrial automation. It aligns with the Structured Text (ST) language defined in the IEC 61131-3 international standard. Beyond its high-level features, SCL incorporates typical PLC elements like inputs, outputs, timers, and block calls, making it suitable for PLC programming. It supports the STEP 7 block concept, allowing for block programming alongside traditional Ladder Logic (LAD) and Function Block Diagram (FBD) methods. This means SCL expands the capabilities of the STEP 7 programming software, offering a more structured and modular approach. SCL promotes code reusability by allowing users to leverage pre-compiled blocks, such as system functions and blocks provided by the CPU's operating system. It also enables seamless integration with LAD and FBD blocks. SCL blocks can call other blocks programmed in LAD or FBD, and vice versa. SCL includes test functions that assist in identifying logical programming errors during compilation, ensuring more robust and reliable program. [6]

```
REGION Motor_1
    REGION "S_1"
        IF "S_1" = TRUE THEN
            "S_2" := FALSE;
            "GB_In001" := TRUE;
            "GB_In003" := 5;
        END_IF;
    END_REGION
    REGION "S_2"
        IF "S_2" = TRUE THEN
             "S_1" := False;
             "GB_In001" := FALSE;
        END_IF;
    END_REGION
END_REGION
```

Figure I.13: *Structured Control Language PLC Programming Example*

Block-Segmented Programming:

The PLC's programming structure is organized into distinct blocks: OBs (Organization Blocks), FCs (Functions), FBs (Function Blocks), and DBs (Data Blocks). This segmented architecture provides a structured and modular approach to managing the controller's program. [7]

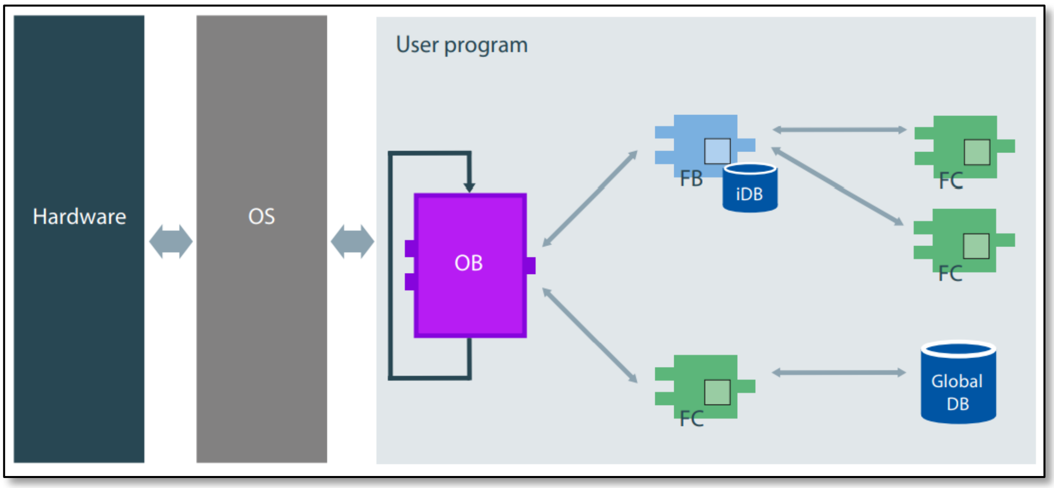


Figure I.14: *TIA Portal Organization Blocks Overview*

- **Organization Block (OB):** OBs represent the primary blocks for managing the execution flow of a PLC program. They are triggered by specific events, such as time intervals or hardware failures. The main OB (OB1) is essential for initializing the program and sequentially calling other blocks, including functions and data blocks. It operates in a continuous cycle, executing the code from beginning to end and then restarting the cycle. This ensures that the PLC consistently processes the programmed instructions. The PLC's sequential execution is controlled by OB1, which dictates the order and timing of these blocks.

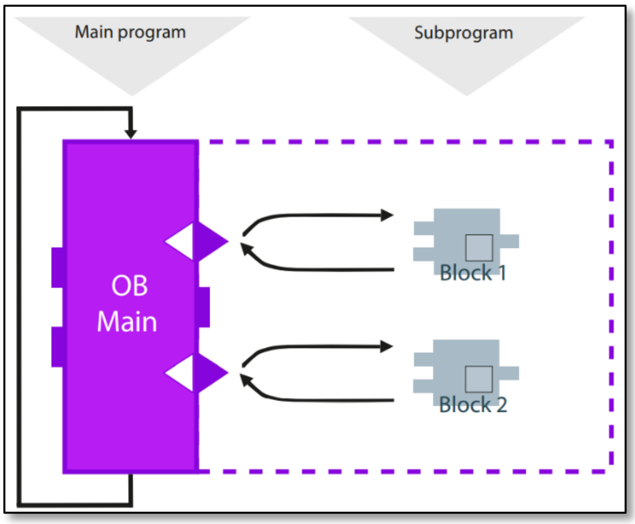


Figure I.15 : *Main Organization Block Operation Diagram*

- **Function (FC):** Functions (FCs) are reusable blocks of code that perform specific tasks. They take input variables, process them according to the defined algorithm, and return output values. FCs can use different types of variables: Input, Output, InOut (input and output), Temporary or constant.
- **Data Block (DB):** Data Blocks (DBs) act as memory storage spaces for data variables within the PLC program. There are two types of DBs:
  - **Global DBs:** These are accessible by all parts of the program, including OBs, FBs, and FCs. They can be used to store data that needs to be shared between different program elements.
  - **Instance DBs (iDBs):** These are associated with specific Function Blocks (FBs).
- **Function Block (FB):** Function Blocks (FBs) are similar to Functions (FCs) in structure, but they have an additional feature: instance Data Blocks (iDBs). Each time an FB is called, a separate iDB is created to store data specific to that instance of the FB.

I.5.1.3. PLC-SIM:

PLC-SIM offers a valuable method to execute, test and debug PLC programs before deploying them into the industrial field. It's key features are:

- **Real-Time Simulation:** PLC-SIM simulates the real-time behavior of a PLC, including its response to inputs and outputs, enabling testing of the automation logic under realistic conditions.
- **Hardware-Independent Simulation:** PLC-SIM allows the simulation various PLC models like the SIMATIC S7-300/400, S7-1200 and S7-1500 series PLCs without requiring the actual hardware. This provides flexibility and cost-effectiveness, as it provides a way to test automation programs on different PLC platforms without investing in physical devices.
- **Integrated Debugging Tools:** PLC-SIM comes with integrated debugging tools that allow the user to step through the program, inspect variables, and analyze program execution flow. This helps identify and resolve errors quickly and efficiently.
- **Visualization and Monitoring:** PLC-SIM provides visualization tools for monitoring the state of the simulated PLC, including input and output signals, internal variables, and program execution status. This allows for a complete understanding of the behavior of the program while being able to identify potential issues.
- **Integration with TIA Portal:** PLC-SIM seamlessly integrates with the TIA Portal environment, enabling the user to use all the features and functionalities of TIA Portal, including program development, configuration, and documentation.

I.5.1.4. SCADA & WinCC:

Supervisory Control and Data Acquisition (SCADA) systems are essential for managing large-scale industrial processes and infrastructure. These systems act as a central hub for gathering, processing, and controlling data from various remote locations. SCADA systems collect data from field devices, such as Remote Terminal Units (RTUs) or Programmable Logic Controllers (PLCs), and centralize it on a supervisory computer. This allows operators to monitor and control the entire process from a single location. Additionally, SCADA provides real-time insights into the status of the process, enabling operators to identify potential problems and take corrective action quickly. [8] The key components of any SCADA system are:

- **PLCs:** PLCs are used in the field for their reliability and ability to be configured to handle specific tasks.
- **Human-Machine Interface (HMI):** The HMI presents data to operators in a user-friendly format, allowing them to monitor and control the process.
- **Supervisory Control System:** This system acquires data from field devices and sends commands to the process based on operator instructions or predefined rules.
- **Communication Infrastructure:** This network connects the supervisory control system to field devices, ensuring reliable data transfer.

The SCADA system utilized in this application is built using the SIMATIC WinCC Professional software. It is a comprehensive SCADA system seamlessly integrated within the TIA Portal environment. It is a PC-based software, providing visualization and control capabilities for processes, production lines, machines, and plants across various industries. It caters very well to this project's application.

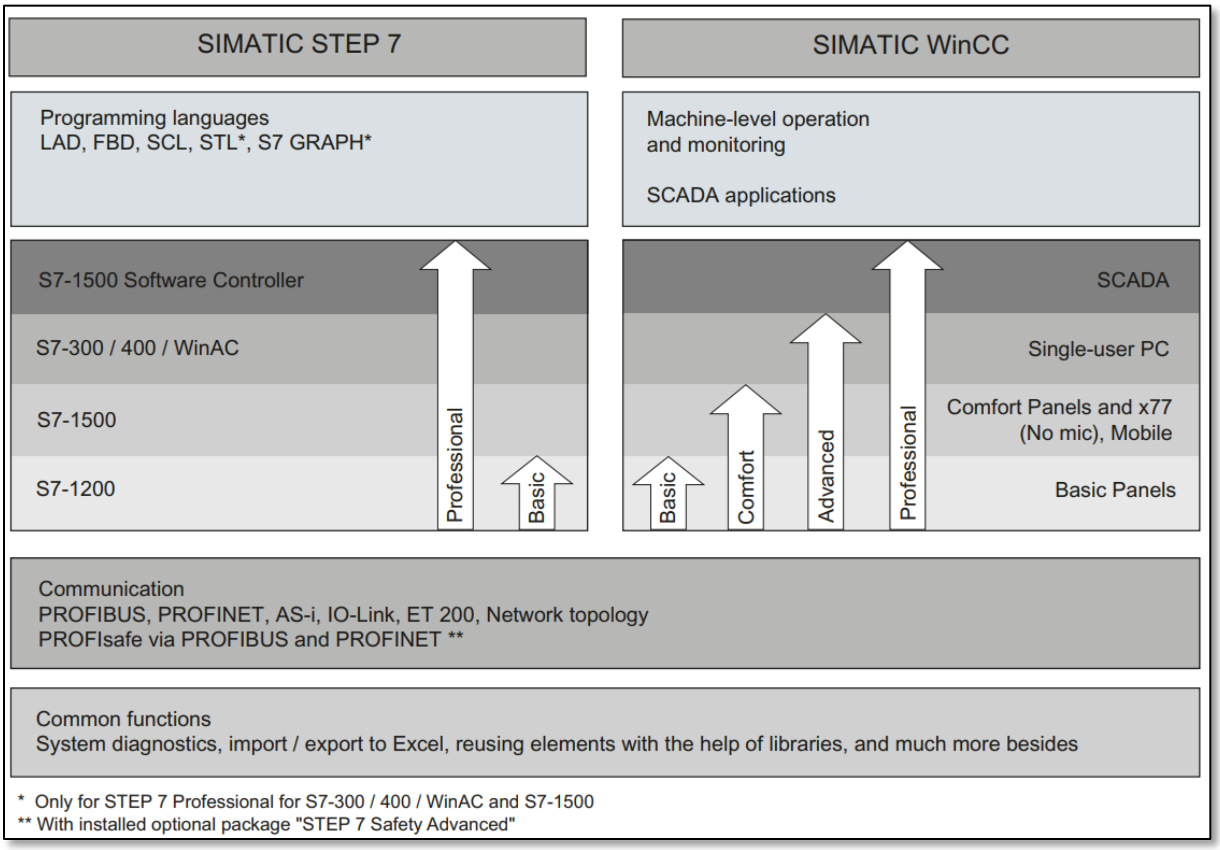


Figure I.16: *SIEMENS SIMATIC Software Integration* [7]

I.5.1.5. NetToPLCSIM:

Nettoplcsim is an open source software that enables the user to connect to the SIEMENS S7-Plcsim PLC simulator over a local network using TCP/IP (Iso-On-TCP) communication. This is achieved through the network interface of the computer running the simulation. This feature is particularly useful for testing client applications, such as SCADA systems or HMIs, alongside S7-Plcsim without requiring an actual PLC. This allows developers to verify the communication and functionality of their client applications in a simulated environment before deploying them with real hardware.

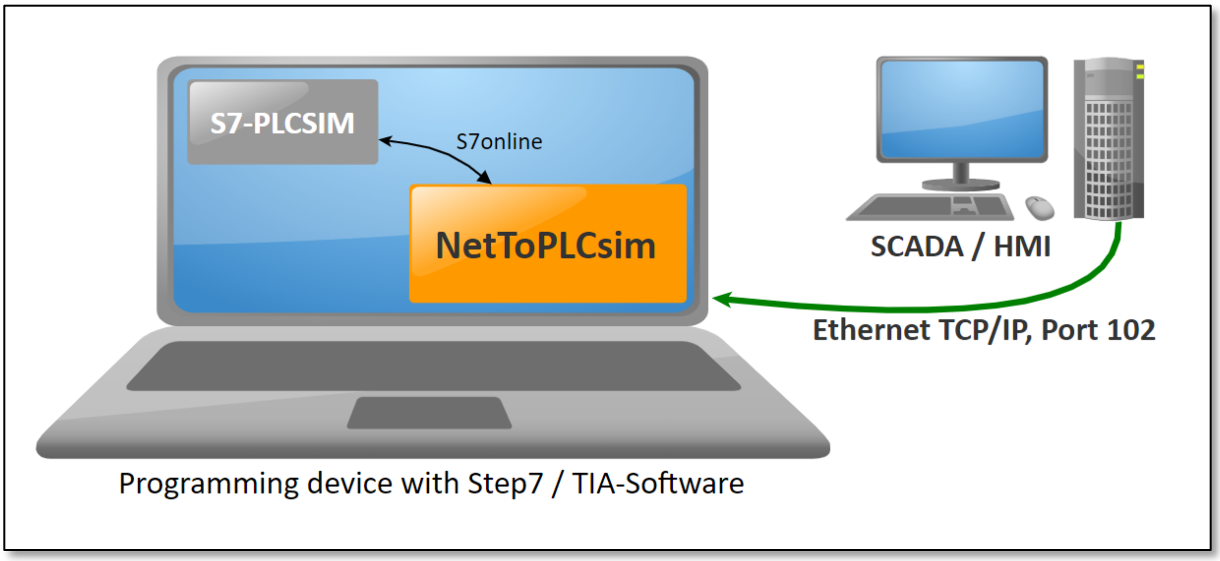


Figure I.17: *NetToPLCsim Integration Diagram* [9]

I.5.1.6. Node Red:

Node-RED is a user-friendly programming tool that enables the user to connect hardware devices, APIs, and online services in efficient ways. Its browser-based editor simplifies the process of building "flows" by dragging and dropping nodes from a vast palette. These flows can be deployed to the runtime with a single click. Node-RED's intuitive interface allows for the creation of JavaScript functions within the editor using a rich text editor. The user is also able to save custom built functions, templates, or entire flows in a built-in library for easy reuse. The lightweight runtime, built on Node.js, leverages its event-driven, non-blocking model, making it ideal for deployment at the edge of the network on low-cost hardware like the Raspberry Pi, as well as in the cloud or even industrial applications utilizing PLCs.

I.5.2. Fire Detection Algorithm Tools:

I.5.2.1. MATLAB:

MATLAB is a programming platform tailored for engineers and scientists. It empowers them to analyze and design complex systems and products as well as data analysis, algorithm development, and model creation. At the core of MATLAB lies its matrix-based programming language, which allows for a natural and efficient expression of complex mathematical computations. [10]

Fuzzy Logic Designer Toolbox:

The Fuzzy Logic Designer Toolbox provided in MATLAB offers a comprehensive set of tools for analyzing, designing, and simulating fuzzy logic systems. It offers MATLAB functions, apps, and Simulink blocks to facilitate this process. Users can define and configure inputs, outputs, membership functions, and rules for both type-1 and type-2 fuzzy inference systems. The toolbox also enables automatic tuning of membership functions and rules based on data, allowing for optimized fuzzy logic system design. Designed fuzzy logic systems can be evaluated within both MATLAB and Simulink environments. Furthermore, the toolbox allows for the use of fuzzy inference systems as a support system for explaining the behavior of black-box AI models. For implementation, the Fuzzy Logic Designer Toolbox enables the generation of standalone executables, C/C++ code, and IEC 61131-3 Structured Text, facilitating the deployment of fuzzy logic systems in various applications. [11]

PLC Coder:

Simulink PLC Coder is used to automatically generate hardware-independent IEC 61131-3 code, specifically Structured Text and Ladder Diagrams, from Simulink models, Stateflow charts, and MATLAB functions. The generated Structured Text code is compatible with popular industry standards, including PLCopen XML and formats supported by leading IDEs such as CODESYS, Studio 5000 and TIA Portal. Simulink PLC Coder also provides tools for verification and validation. It generates test benches to ensure the accuracy of the generated Structured Text and Ladder Diagrams using both PLC and PAC IDEs and simulation tools. Additionally, it produces code generation reports with static code metrics and bidirectional traceability between the original model and the generated code. [12]

I.5.2.2. Fire Dynamics Simulator (FDS):

The Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model developed by the National Institute of Standards and Technology (NIST) for the simulation of fire-driven fluid flow. This software tool is widely used in the fire protection engineering industry to analyze the behavior of fires and the performance of fire alarm systems. The FDS software utilizes numerical techniques to model the transport of smoke and heat from fires, providing valuable insights into the complex dynamics of fire events. By inputting detailed information about the physical environment, fuel sources, and ventilation conditions, engineers can predict the spread of fires, the development of smoke layers, and the effectiveness of fire suppression systems. A visualization of the undertaken simulation can be rendered using SmokeView (SMV) which is an add-on program used to display the output of FDS. [13]

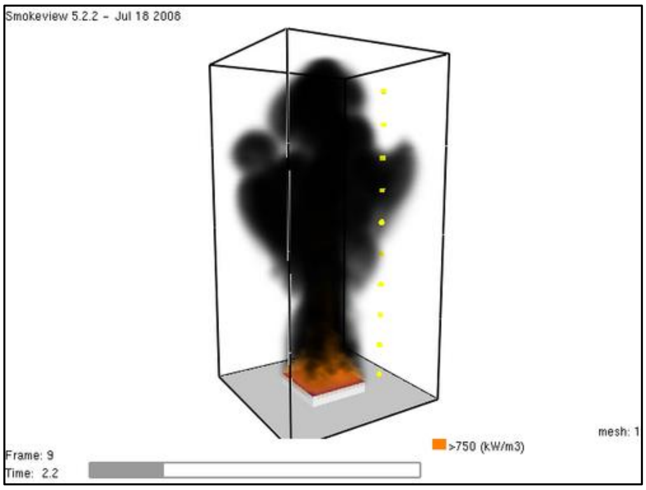


Figure I.18: *FDS & SmokeView Output Example*

One of the key applications of the Fire Dynamics Simulator is in the design and evaluation of fire alarm systems. By simulating fire scenarios, engineers can assess the placement and performance of smoke detectors, heat detectors, and other fire alarm components, ensuring that the system is optimized to provide early warning and effective response in the event of a fire emergency.

I.6. Conclusion:

This chapter has established the theoretical underpinnings and introduced the key tools necessary for developing intelligent fire detection and fire-fighting systems. With this groundwork in place, the project application’s detailed description can be considered.

- CHAPTER II -

System Description

II.1. Introduction:

This chapter provides a comprehensive description of the fire safety system under development, focusing on the fire-fighting equipment and pumping systems across the three fire zones: Administrative, Industrial, and Sea zones. It presents an overview of the system and delves into the specific components and instrumentation of the pumping system, including sensors (pressure transmitters, level transmitters), actuators (fire pumps, valves, foam proportioner …), and a summary of system inputs and outputs. Understanding the intricate details of this fire safety system provides a reference for developing the smart fire detection and response solution explored in the subsequent chapter.

II.2. Fire Safety System Overview:

The figure II.1 below provides a comprehensive overview of the entire fire safety system, including the implementation methods for each of its sub-systems.

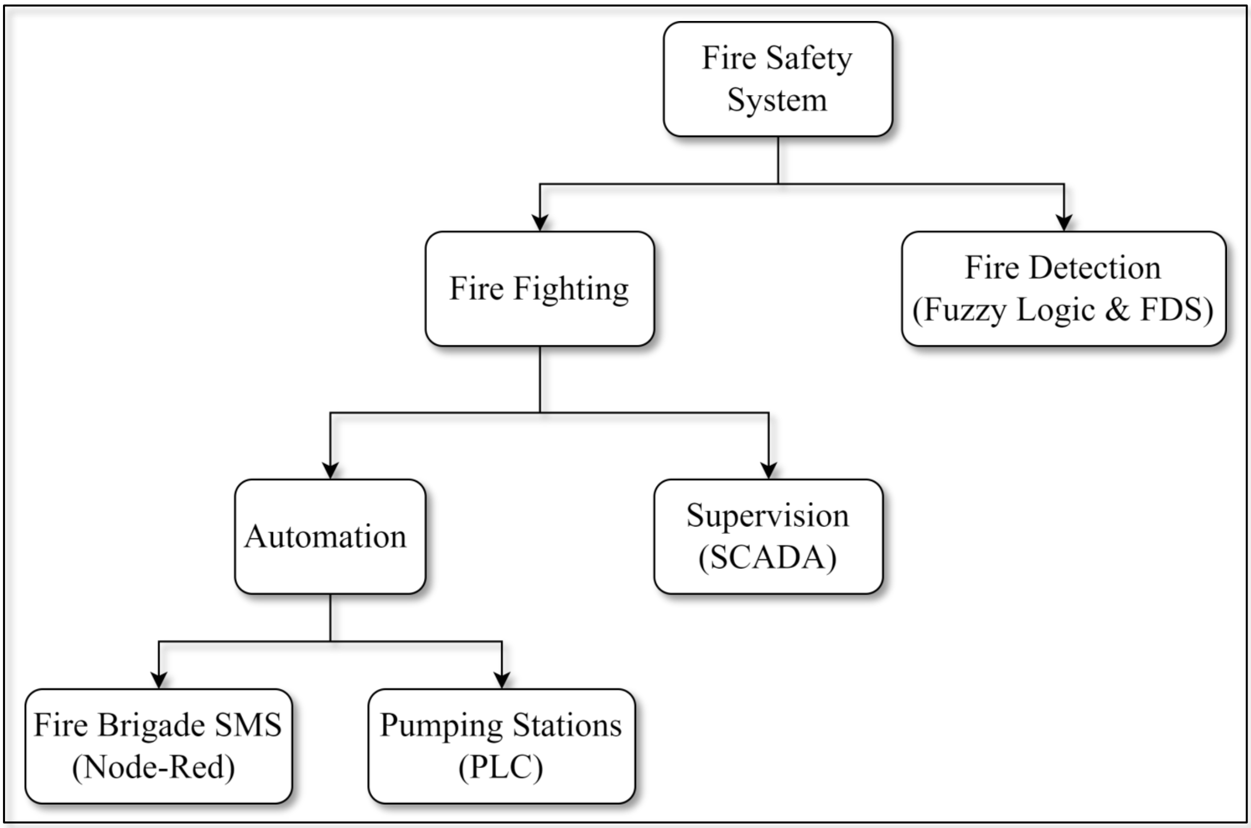


Figure II.1: *Fire Safety System Overview Diagram*

This fire safety system is designed for an oil and gas industrial facility comprising three distinct zones: administrative fire zone, industrial fire zone, and a sea zone, each serving a predefined function in each of their respective sector within the industrial complex.

The Administrative zone includes the administrative office building. This zone includes two sub-systems which are the fire detection system and the fire-fighting pumping system. The fire detection system provides early fire incident warning for this zone. This system includes smoke, heat, flame and CO (Carbon Monoxide) detectors in addition to manual call points all interconnected to the main control unit (PLC). The fire detection system ensures early fire incident warning so that the occupants are able to evacuate the area as soon as possible as well as ensuring an immediate response from the fire-fighting personnel, thus reducing the fire spread and damage as well as improving the safety in case of fire and other potential hazards for the occupants. The pumping system ensures an adequate water supply and provides the necessary hydraulic pressure and flow to the fire-fighting devices which are installed within the administrative building. The pumping system includes:

- Two jockey pumps
- One well pump
- One electric pump set
- One diesel pump set
- Diesel fuel tank
- Water storage tank
- Sprinklers
- Deluge valves

The industrial zone involves higher fire risks due to the presence of flammable materials and industrial processes. To counter these risks, this zone is provided with more robust fire-fighting pumping system. This system resembles the system implemented in the administrative zone but is scaled to meet the more demanding requirements of the industrial environment. Also, foam is mixed to water and used as a second kind of extinguishing agent. This zone's pumping system includes:

- One well pump
- Two jockey pumps
- One electric pump set

- One diesel pump set
- Diesel fuel tank
- Foam proportioner
- Foam bladder tank
- Water storage tank
- Sprinklers
- Deluge valves
- 28 Fire hydrants
- 8 Pressure release valves

The sea zone is a support zone for both the administrative fire zone and the industrial fire zone. It has its own pumping station, which plays a supplementary role in providing water; especially in case of failure of the two other fire zones' systems. The pumping equipment in this zone is supplied directly from seawater, which guarantees sufficient and uninterrupted supply. This zone constitutes a redundant and supportive system thereby enhancing the total fire-fighting capability of the facility. This zone includes:

- Two jockey pumps
- One electric pump set
- One diesel pump set
- Diesel fuel tank
- Sprinklers
- Deluge valves

This overview provided a high-level understanding of the system's structure. Subsequent sections will delve deeper into the specifics of each zone along with the operational integration between them.

II.3. Pumping System Components & Instrumentation:

II.3.1. Sensors:

II.3.1.1. Pressure transmitter:

A pressure transmitter is a sensing device that measures then converts water pressure into an electrical signal. It is widely used in industrial applications to measure water pressure in pipes, tanks, and other water systems. For instance, it is used to monitor, control and sequence the operation of the fire pumps.

Water pressure transmitters can measure different types of pressure:

- **Absolute pressure:** The total pressure exerted by the water, including atmospheric pressure.
- **Gauge pressure:** The pressure of the water relative to the atmospheric pressure.
- **Differential pressure:** The difference in pressure between two points in the water system.

The electrical signal output by the transmitter is typically an analog current (4-20mA) or voltage (0-5V) signal.

Working Principle:

The core of the transmitter is a pressure sensing element, typically a diaphragm or a strain gauge. This element deforms proportionally to the force of the applied water pressure. The deformation of the sensing element is then converted into an electrical signal through the change in resistance of a semiconductor material or the change in capacitance for a capacitive transducer.

Choice Criteria:

Several factors have to be considered for the choice of the adequate pressure transmitter, such as:

- **Pressure Range:** Maximum and minimum pressure to be measured by the transmitter.
- **Accuracy:** Required level of accuracy for the application i.e. the measurement error has to be minimal.
- **Output Signal:** Type of signal required by the monitoring and control system.
- **Environmental Conditions:** Temperature, humidity and other environmental conditions where the transmitter will be installed.
- **Material Compatibility:** Materials of construction of the transmitter have to be compatible with the water to be measured.

According to these criteria, the selected pressure transmitter was the Kavlico P1A.

Characteristics:

Pressure Range	0 to 16 Bar (guage & absolute)
Accuracy	≤ 1 %
Operating Supply Signal	9 – 30 VDC
Ingress Protection	IP65 or IP67 (depending on electrical connector)
Housing Material	Stainless Steel
Output Signal	4 to 20 mA or 0.5 to 4.5 VDC

Table II.1: *Kavlico P1A Pressure Transmitter Characteristics* [14]

Figure II.2: *Kavlico P1A Pressure Transmitter* [14]

Applications:

A pressure transmitter is used:

- In the common discharge line in the administrative, industrial and sea fire zones.
- In the tank filling line from the well in the administrative and industrial fire zones.
- At the outputting ends of the 28 fire hydrants in the industrial zone.
- At the outputting ends of the 8 pressure relief valves in the industrial zone.

II.3.1.2. Hydrostatic level transmitter:

A hydrostatic level sensor, also known as a submersible level sensor, is a device that measures the level of a liquid by converting the hydrostatic pressure at the bottom of the liquid storage tank into an electrical signal.

Working Principle:

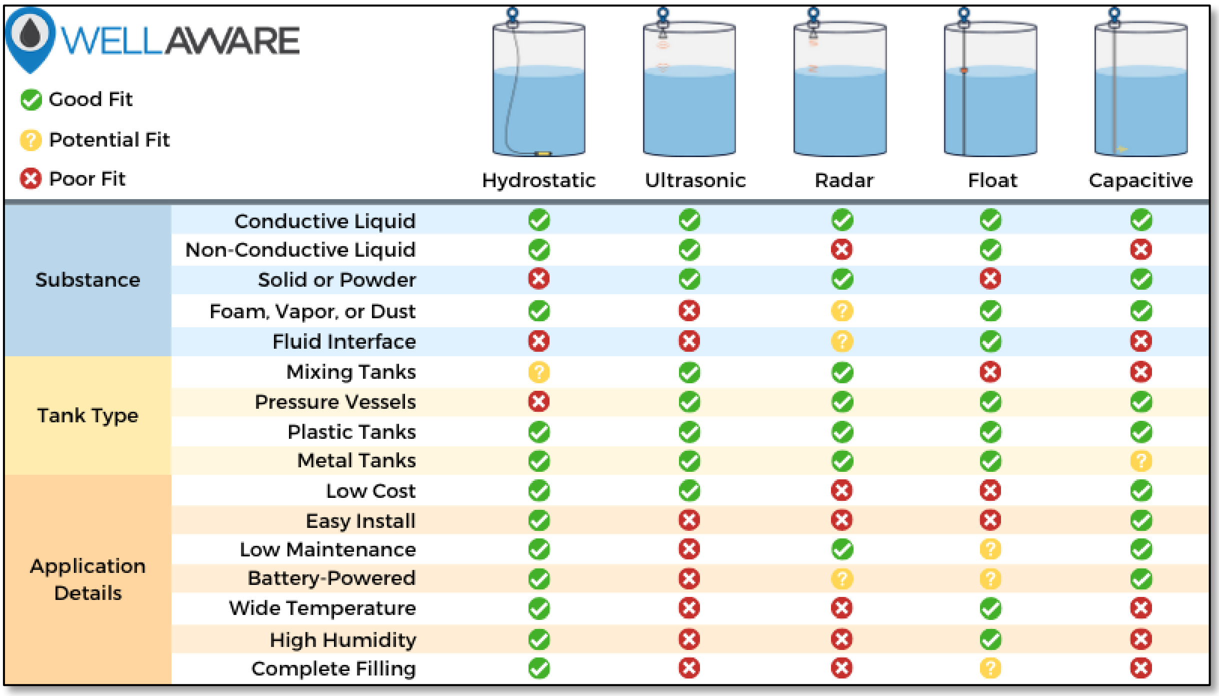
The pressure at the bottom of a liquid storage tank is directly proportional to the height of the liquid column and its density according to equation (II.1). This is defined as the hydrostatic pressure. This latter is measured by a diaphragm then converted into an electrical signal.

$$P = \rho . g . h \quad ... (\mathbf{II.1})$$

- P is the hydrostatic pressure in **N/m^2**.
- ρ is the density of the fluid in **kg/m^3**.
- g is the acceleration due to gravity in **m/s^2**.
- h is height of the liquid column in **m**.

Choice Criteria:

The following chart summarizes the important choice criteria for a level sensor:



		Hydrostatic	Ultrasonic	Radar	Float	Capacitive
Substance	Conductive Liquid	✓	✓	✓	✓	✓
	Non-Conductive Liquid	✓	✓	✗	✓	✗
	Solid or Powder	✗	✓	✓	✗	✓
	Foam, Vapor, or Dust	✓	✗	?	✓	✓
	Fluid Interface	✗	✗	?	✓	✗
Tank Type	Mixing Tanks	?	✓	✓	✗	✗
	Pressure Vessels	✗	✓	✓	✓	✓
	Plastic Tanks	✓	✓	✓	✓	✓
	Metal Tanks	✓	✓	✓	✓	?
Application Details	Low Cost	✓	✓	✗	✗	✓
	Easy Install	✓	✗	✗	✗	✓
	Low Maintenance	✓	✗	✓	?	✓
	Battery-Powered	✓	✗	?	?	✓
	Wide Temperature	✓	✗	✗	✓	✗
	High Humidity	✓	✗	✗	✓	✗
	Complete Filling	✓	✗	✗	?	✗

Figure II.3: *Level sensor choice criteria* [15]

According to these criteria, the selected level transmitter was of the hydrostatic type, more specifically: the Rocksensor RP202L.

Characteristics:

Level Range	0 ~ 0.5m to 200m
Accuracy	≤ 0.5 %
Operating Supply Signal	14 – 36 VDC
Ingress Protection	IP68
Probe Material	Stainless Steel
Output Signal	4 to 20 mA

Table II.2: *Rocksensor RP202L Level Transmitter Characteristics* [16]

Figure II.4: *Rocksensor RP202L Level Transmitter* [16]

Applications:

A hydrostatic level transmitter is used:

- Inside the water storage tank in the administrative and industrial fire zones.
- Inside the diesel fuel tank in the administrative, industrial and sea fire zones.
- Inside the foam bladder tank in the industrial fire zone.

II.3.2. Actuators:

II.3.2.1. Electric Fire Pumps:

There are 2 types of electric fire pumps that are utilized as the primary hydraulic set for each zone's pumping system: low flow rate and high flow rate electric fire pumps.

Low flow rate electric fire pump:

This fire pump set consists of a horizontal split-case centrifugal pump (HSEF 4-12), a 4-pole 50Hz electric motor (MMG 280M-E) and a controller. Pump and motor are mounted on common base frame and connected by a flexible coupling. This pump set is used in the administrative fire zone only.

Characteristics:

Flow Rate	500 GPM (113 m^3/h)
Operating Pressure	104 to 173 PSI
Electric Motor Power	90 KW
Inlet Pressure	5 to 7 PSI
Construction Material	Stainless Steel

Table II.3: *Grundfos HSEF 4-12 Electric Fire Pump Set Characteristics* [17]

Figure II.5: *Grundfos HSEF 4-12 Electric Fire Pump Set* [17]

Program Reference	Inputs	Outputs
Z1-EFP-A	Operating State (ON/OFF)	Pump Failure State
	Electric Generator State	Electric Motor State
	Operating Mode Switch (AUTO/MANUAL)	/

Table II.4: *Inputs & Outputs of the Administrative Fire Zone's Electric Pump Set*

High flow rate electric fire pump:

This fire pump set also consists of a horizontal split-case centrifugal pump (HSEF 12-19G), a 4-pole 50Hz electric motor (Siemens 355) and a controller. Pump and motor are mounted on common base frame and connected by a flexible coupling. This pump set is used in the Industrial and sea fire zones.

Characteristics:

Flow Rate	4500 GPM (1022 m^3/h)
Operating Pressure	108 to 177 PSI
Electric Motor Power	355 KW
Inlet Pressure	5 to 7 PSI
Construction Material	Stainless Steel

Table II.5: *Grundfos HSEF 12-19G Electric Fire Pump Set Characteristics* [18]

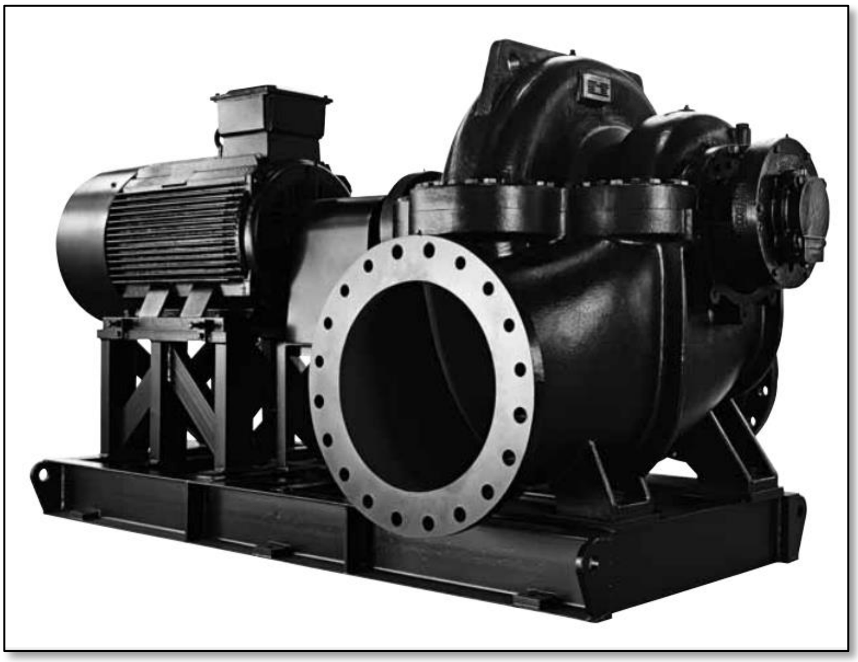


Figure II.6: *Grundfos HSEF 12-19G Electric Fire Pump Set* [18]

Program Reference	Inputs	Outputs
Z2-EFP-A (Industrial Zone) **SZ-EFP-A (Sea Zone)**	Operating State (ON/OFF)	Pump Failure State
	Electric Generator State	Electric Motor State
	Operating Mode Switch (AUTO/MANUAL)	/

Table II.6: *Inputs & Outputs of the Industrial and Sea Fire Zones' Electric Pump Set*

II.3.2.2. Diesel Fire Pumps:

Similarly to the electric fire pumps, there are 2 types of diesel fire pumps that are utilized as the secondary hydraulic set for each zone's pumping system: low flow rate and high flow rate diesel fire pumps.

Low flow rate diesel fire pump:

This fire pump set consists of a horizontal split-case centrifugal pump (HSEF 4-12), a 6 cylinder diesel-powered engine (JU6H-UF30) with a 12 VDC, 42 ampere alternator and a controller. Pump and engine are mounted on common base frame. This pump set is used in the administrative fire zone only.

Characteristics:

Flow Rate	500 GPM (113 m^3/h)
Operating Pressure	104 to 173 PSI
Rotation Speed	1760 RPM
Diesel Engine Power	104 KW
Inlet Pressure	5 to 7 PSI
Construction Material	Stainless Steel

Table II.7: *Grundfos HSEF 4-12 Diesel Fire Pump Set Characteristics* [19]

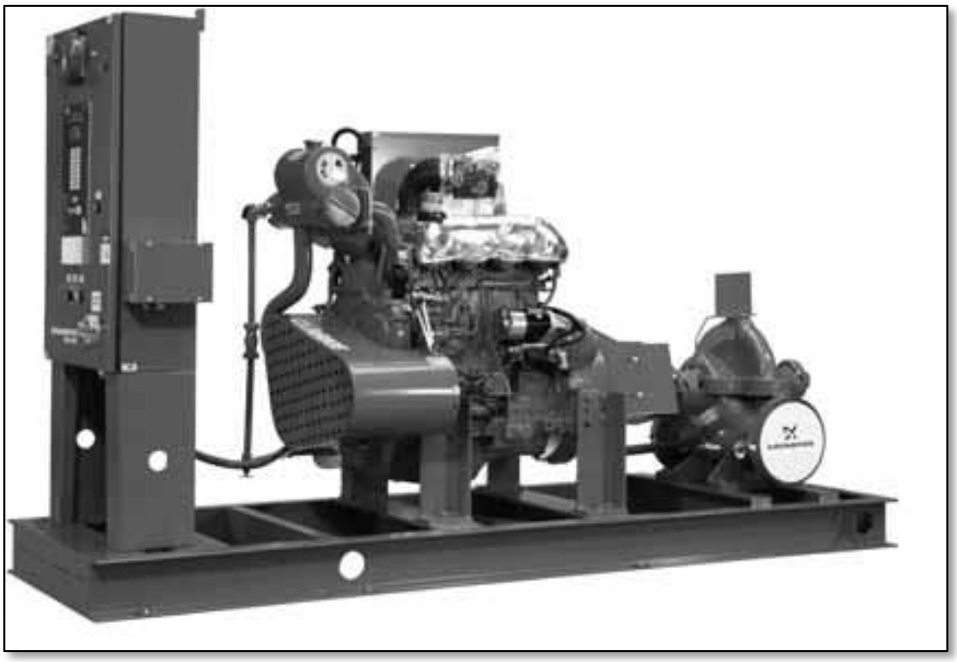


Figure II.7: *Grundfos HSEF 4-12 Diesel Fire Pump Set* [19]

Program Reference	Inputs	Outputs
Z1-DFP-B	Operating State (ON/OFF)	Pump Failure State
	Operating Mode Switch (AUTO/MANUAL)	Low Diesel Level Indicator

Table II.8: *Inputs & Outputs of the Administrative Fire Zone's Diesel Pump Set*

High flow rate diesel fire pump:

Similarly to the low flow diesel fire set, this diesel fire pump set consists of a horizontal split-case centrifugal pump (HSEF 10-16), a 6 cylinder diesel-powered engine (JX6H-UF30) with a 24 VDC, 40 ampere alternator and a controller. Pump and engine are mounted on common base frame. It is used in the Industrial and sea fire zones.

Characteristics:

Flow Rate	4000 GPM (908 m^3/h)
Operating Pressure	108 to 177 PSI
Rotation Speed	1760 RPM
Diesel Engine Power	313 KW
Inlet Pressure	5 to 7 PSI
Construction Material	Stainless Steel

Table II.9: *Grundfos HSEF 10-16 Diesel Fire Pump Set Characteristics* [19]

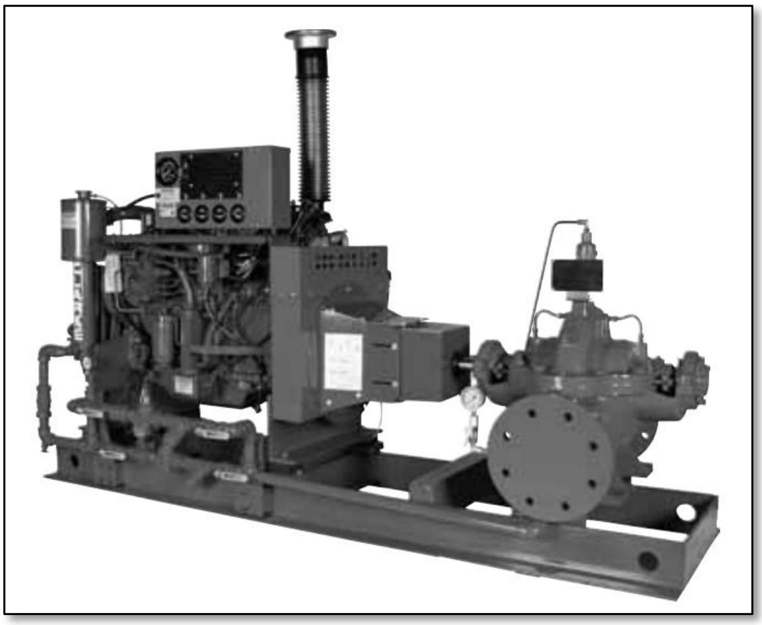


Figure II.8: *Grundfos HSEF 10-16 Diesel Fire Pump Set* [19]

Program Reference	Inputs	Outputs
Z2-DFP-B (Industrial Zone) SZ-DFP-B (Sea Zone)	Operating State (ON/OFF)	Pump Failure State
	Operating Mode Switch (AUTO/MANUAL)	Low Diesel Level Indicator

Table II.10: *Inputs & Outputs of the Industrial and Sea Fire Zones' Diesel Pump Set*

II.3.2.3. Jockey Pumps:

A jockey pump is a small, electrically powered pump used to maintain constant pressure within the system's water supply. It is essentially a "top-up" pump that keeps the pressure consistent, ensuring that the main discharge outlets as well as the sprinkler system can activate quickly and effectively in the event of a fire. Each fire zone has 2 jockey pumps: a primary and a secondary jockey pump. Similarly to the main fire pumps, there are 2 types of jockey pumps that are utilized for each zone's pumping system: low flow rate and high flow rate jockey pumps.

Low flow rate jockey pump:

This jockey pump is a vertical multistage centrifugal pump, more specifically, the GRUNDFOS CR1s. The pump consists of a base and a pump head. The base has inlet and outlet ports on the same level (in-line). A set of 2 low flow jockey pumps are used in the administrative fire zone only.

Characteristics:

Nominal Flow Rate	4.5 GPM (1 m^3/h)
Max. Working Pressure	362 PSI
Max. Pump Efficiency	35 %
Motor Power	0.33 to 2 HP
Construction Material	Cast Iron and Stainless Steel

Table II.11: *Grundfos CR 1s Jockey Pump Characteristics* [20]

Figure II.9: *Grundfos CR 1s Jockey Pump* [20]

Program Reference	Inputs	Outputs
Z1-JP1-A (Primary) **Z1-JP2-B (Secondary)**	Operating State (ON/OFF)	Pump Failure State
	Operating Mode Switch (AUTO/MANUAL)	/

Table II.12: *Inputs & Outputs of the Administrative Fire Zone's Jockey Pumps*

High flow rate jockey pump:

This jockey pump is a vertical multistage centrifugal pump, more specifically, the GRUNDFOS CR10. The pump consists of a base and a pump head. The base has inlet and outlet ports on the same level (in-line). A set of 2 high flow jockey pumps are used in the administrative and sea fire zones.

Characteristics:

Nominal Flow Rate	55 GPM (12.5 m^3/h)
Max. Working Pressure	362 PSI
Max. Pump Efficiency	70 %
Motor Power	0.75 to 15 HP
Construction Material	Cast Iron and Stainless Steel

Table II.13: *Grundfos CR 10 Jockey Pump Characteristics* [20]

Figure II.10: *Grundfos CR 10 Jockey Pump* [20]

<table>
<tr><th>Program Reference</th><th>Inputs</th><th>Outputs</th></tr>
<tr><td rowspan="2"><u>Industrial zone</u>:
Z1-JP1-A (Primary)
Z1-JP2-B (Secondary)
<u>Sea Zone</u>:
SZ-JP1-A (Primary)
SZ-JP2-B (Secondary)</td><td>Operating State (ON/OFF)</td><td>Pump Failure State</td></tr>
<tr><td>Operating Mode Switch (AUTO/MANUAL)</td><td>/</td></tr>
</table>

Table II.14: *Inputs & Outputs of the Industrial and Sea Fire Zone's Jockey Pumps*

II.3.2.4. Well Pumps:

A well pump is a special type of pump used to extract water from a well and push it into the water storage tank. It ensures a consistent supply of water independent of municipal networks. Submersible pumps are the main type of well pumps used in the industrial setting due to their practicality in most well types. The specific brand used here is the SULZER ABS VUPX 0403 which is a submersible three-blade propeller axial-flow vertical pump powered by an electric motor. A single well pump is utilized in each of the administrative and industrial fire zones.

Characteristics:

Capacity	2000 l/s
Max. Working Pressure	600 PSI
Max. Head Depth	20 m
Motor Power	150 KW
Mains Motor Voltage	460 V (60Hz)
Construction Material	Heavy Duty Stainless Steel

Table II.15: *SULZER ABS VUPX 0403 Well Pump Characteristics* [21]

Figure II.11: *SULZER ABS VUPX 0403 Well Pump* [21]

Program Reference	Inputs	Outputs
Z1-WP (Administrative Zone) **Z2-WP (Industrial Zone)**	Operating State (ON/OFF)	Pump Failure State
	Operating Mode Switch (AUTO/MANUAL)	Well Water Level Alarm

Table II.16: *Inputs & Outputs of the Administrative and Industrial Zone's Well Pump*

II.3.2.5. Deluge Valves:

A deluge valve is a type of valve used in fire sprinkler systems that allows a large volume of water to flow quickly into a specific area when activated. Unlike standard sprinkler heads that activate individually, a deluge valve opens all sprinkler heads in a designated sector simultaneously, creating a "deluge" of water. It is used in the pumping system's room of each fire zone.

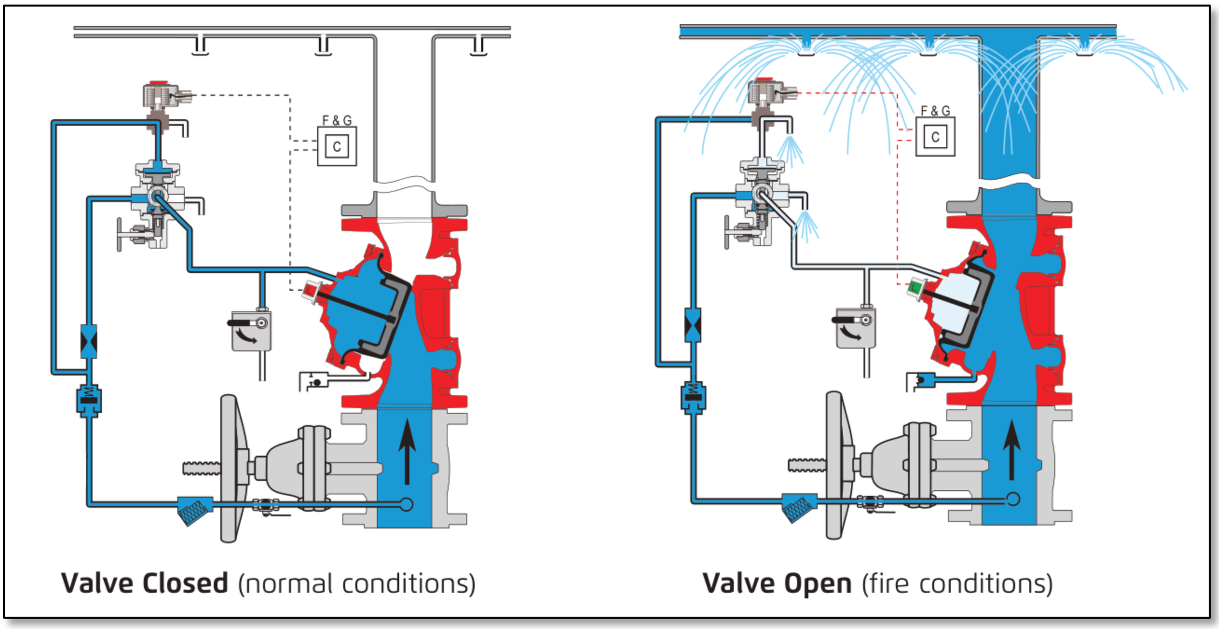


Figure II.12: *Deluge Valve Operation* [22]

A three-way solenoid valve receives the actuating signal from the PLC and activates a latching relay valve, which in turn opens the main valve allowing water to flow. The deluge valve model employed in this application is the BERMAD FP 400Y-3UM electrically controlled deluge valve with local reset.

Characteristics:

Pressure Rating	25 Bar (365 PSI)
Temperature Rating	60 °C
Construction Material	Stainless Steel

Table II.17: *BERMAD FP 400Y-3UM Deluge Valve Characteristics* [22]

Figure II.13: *BERMAD FP 400Y-3UM Deluge Valve* [22]

Inputs	Outputs
Operating State (OPEN/CLOSE)	Valve Failure State
/	Operating Mode Switch (AUTO/MANUAL)

Table II.18: *Inputs & Outputs of the Deluge Valves*

II.3.2.6. Electrically Actuated Valves:

Electric actuated valve uses power-to-open and power-to-close ball. In case of power cutoff, it stays in the last known position. The motor is actuated by a continuous voltage signal, causing a 90-degree rotation of the ball. Internal cams engage limit switches, providing a mechanical stop for the motor. A reversed continuous signal reverses the motor's rotation, returning the valve to its initial state. The brand and model used in the piping system is the Valworkx 563832E.

Characteristics:

Max. Pressure Rating	19 Bar
Power Supply	240 VDC/VAC
Cycle Time	58 sec
Enclosure Rating	IP67

Table II.19: *Valworkx 563832E Electrically Actuated Valve Characteristics* [23]

Figure II.14: *Valworkx 563832E Electrically Actuated Valve* [23]

Inputs	**Outputs**
Operating State (OPEN/CLOSE)	Valve Failure State
/	Operating Mode Switch (AUTO/MANUAL)

Table II.20: *Inputs & Outputs of the Electrically Actuated Valve*

Application:

An electrically actuated valve is utilized in:

- The common discharge line in each fire zone. For the sea fire zone, a single one is installed in each output line leading to both the administrative and the industrial zones (2 valves in total).
- The filling pipe connecting the well pump to the water tank in the administrative and industrial zones.
- The feedback pipes for every fire pump of each fire zone (2 for each zone, 6 in total).

II.3.2.7. Foam Proportioner:

A foam proportioner is a device used to accurately mix foam concentrate with water, creating a double extinguishing agent solution. There are various types of foam proportioners, including in-line proportioners, eductor proportioners, and balanced pressure proportioners. For this application purpose, the FireDos FD10000 GEN III foam proportioner was chosen. It is utilized exclusively in the industrial fire zone.

Characteristics:

Max. Flow Rate	10000 l/min
Operating Pressure	5 to 16 Bar
Proportioning Rate	1%
Construction Material	Stainless Steel and Cast Aluminum

Table II.21: *FireDos FD10000 GEN III Foam Proportioner Characteristics* [24]

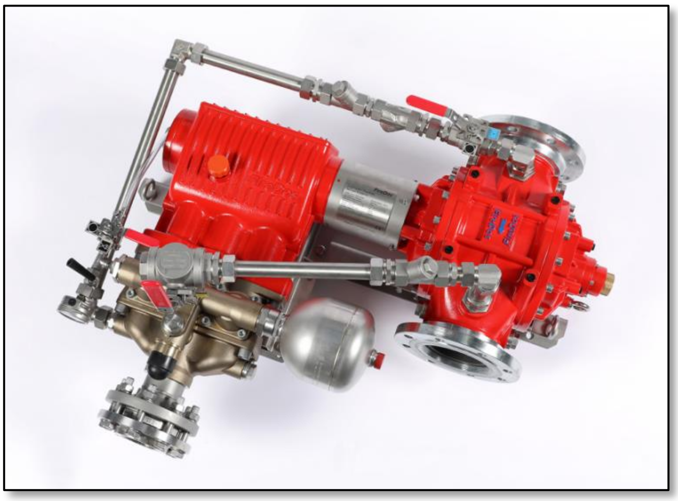


Figure II.15: *FireDos FD10000 GEN III Foam Proportioner [24]*

Inputs	Outputs
Operating State (ON/OFF)	Motor Failure State

Table II.22: *Inputs & Outputs of the Foam Proportioner*

II.3.2.8. Pressure Relief Valves:

A pressure relief valve (PRV) is a safety device designed to automatically vent excess pressure from the pumping system to prevent damage or failure. It is essentially a valve that opens when pressure exceeds a predetermined threshold; allowing fluid to escape and relieve the pressure buildup. The brand model employed is the BERMAD 43T.8 of these valves are exclusively utilized in the industrial fire zone.

Characteristics:

Max. Flow Rate	10000 l/min
Operating Pressure	5 to 16 Bar
Proportioning Rate	1%
Construction Material	Stainless Steel and Cast Aluminum

Table II.23: *BERMAD 43T Pressure Relief Valve Characteristics [25]*

Figure II.16: *BERMAD 43T Pressure Relief Valve* [25]

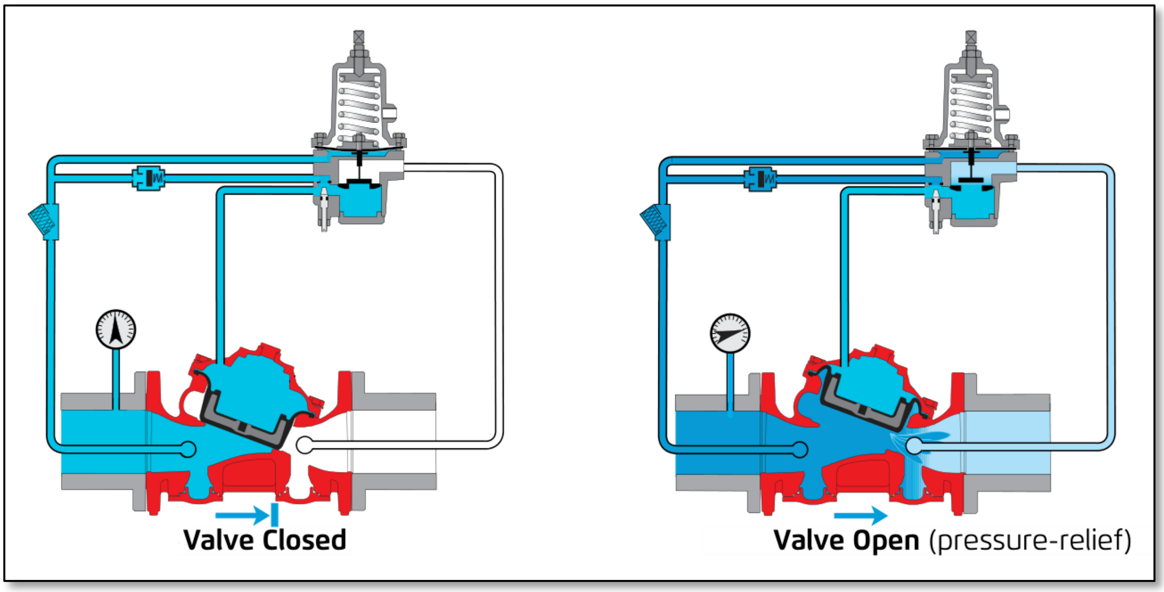


Figure II.17: *Pressure Relief Valve Operation* [25]

II.4. Summary of Pumping Systems Inputs & Outputs:

Fire Zone	Component	Qty.	No. of Inputs	Total No. of Inputs	No. of Outputs	Total No. of Outputs
Administrative	Jockey Pump	2	2	4	1	2
	Electric Pump	1	3	3	2	2
	Diesel Pump	1	2	2	2	2
	Well Pump	1	2	2	2	2
	Deluge Valve	1	1	1	2	2
	Elec. Actuated Valve	4	1	4	2	8
	Pressure Transmitter	2	0	0	1	2
	Level Transmitter	2	0	0	1	2
Industrial	Jockey Pump	2	2	4	1	2
	Electric Pump	1	3	3	2	2
	Diesel Pump	1	2	2	2	2
	Well Pump	1	2	2	2	2
	Foam Proportioner	1	1	1	1	1
	Deluge Valve	1	1	1	2	2
	Elec. Actuated Valve	4	1	4	2	8
	Pressure Relief Valve	8	0	0	1	8
	Pressure Transmitter	38	0	0	1	38
	Level Transmitter	3	0	0	1	3
Sea	Jockey Pump	2	2	4	1	2
	Electric Pump	1	3	3	2	2
	Diesel Pump	1	2	2	2	2
	Deluge Valve	1	2	2	2	2
	Elec. Actuated Valve	4	1	4	2	8
	Pressure Transmitter	1	0	0	1	1
	Level Transmitter	1	0	0	1	1
Total				**48**		**108**

Table II.24: *Summary of Pumping Systems Inputs & Outputs*

II.5. Conclusion:

This chapter has provided a comprehensive description of the fire safety system, detailing the fire-fighting equipment, pumping systems, components, and instrumentation across the Administrative, Industrial, and Sea zones. By examining each system component, a thorough understanding of this complex infrastructure has been established.

- CHAPTER III -

Automation & Supervision Solution

III.1. Introduction:

This chapter presents the automation and supervision solution developed for the fire-fighting pumping system. In the automation section, the choice of the PLC model is discussed along with the PLC configuration, automation program logic illustrated with flowcharts as well as the SMS notification implementation. In the supervision section, the SCADA system design is explained through all the graphical user interface views.

III.2. Automation Solution:

The automation solution of this project was developed using TIA Portal V14 and SIMATIC WinCC Professional.

III.2.1. Choice of PLC:

A fire safety system must be highly reliable, ensuring uninterrupted availability and minimizing the risk of failures or downtime, as even momentary lapses could have catastrophic consequences. To meet these requirements, a fail-safe PLC with redundancy features must be selected to ensure the fire safety system remains operational at all times. Its key feature is the possibility to develop a safety program using TIA Portal's provided libraries along with utilizing fail-safe I/O modules.

Feature	Standard PLC	Fail-Safe PLC
Primary Purpose	Automate machine processes, functions, and production lines	Provide both automation and safety functions in one device
Safety Functions	Typically developed independently	Integrated safety protocols and functions
Machine Safety	Not the primary focus	High priority, designed for improved safety implementation
Failure Mode	Can fail in unpredictable ways	Fails in a protective and predictable manner
Failure Response	Can lead to potential harm	Initiates a safe shutdown to avoid harm to people or processes
Diagnostics	Standard diagnostics	Built-in diagnostics to continuously monitor inputs/outputs

Table III.1: *Comparison Chart between Standard PLC and Fail-Safe PLC*

Specifically, the Siemens S7-1516F PLC has been selected. It is a modular CPU with standard and fail-safe I/O module support.

Figure III.1: *SIEMENS S7-1516F PLC*

Here are some essential characteristics:

General Information	
Product Type Designation	CPU 1516F-3 PN/DP
Supply Voltage	24 V DC
Fail-Safe	Yes
Memory	
Integrated	6.5 Mbyte
Integrated (for program)	1.5 Mbyte
Integrated (for data)	5 Mbyte
Interface Module (IM)	
Number of Connectable IMs (max)	32; CPU + 31 modules
Communication Protocols	
IP Protocol	Yes, IPv4
PROFINET IO Controller	Yes
SIMATIC Communication	Yes

Table III.2: *Basic Characteristics of the S7-1516F PLC* [26]

For the PLC configuration, a single F-DI (fail-safe digital input) module and a single F-DQ (fail-safe digital output) module have been added along with a 25W power supply. Additionally, an AI (analog input) module is added to extend the number of available analog inputs. For the device configuration, the PROFINET communication protocol is utilized to establish the connection between the PLC and the SCADA system's SIMATIC PC Station.

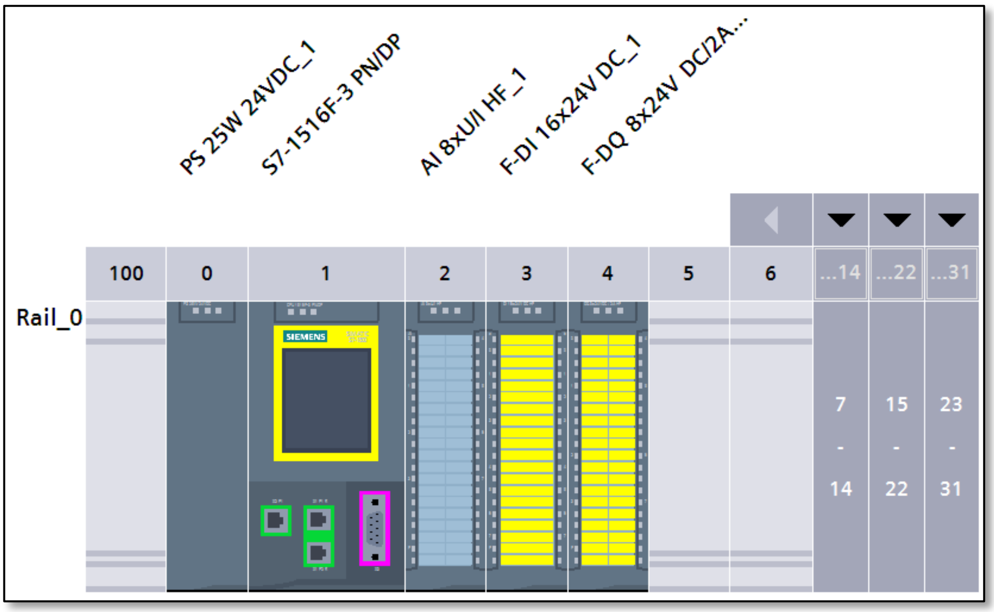


Figure III.2: *PLC Configuration*

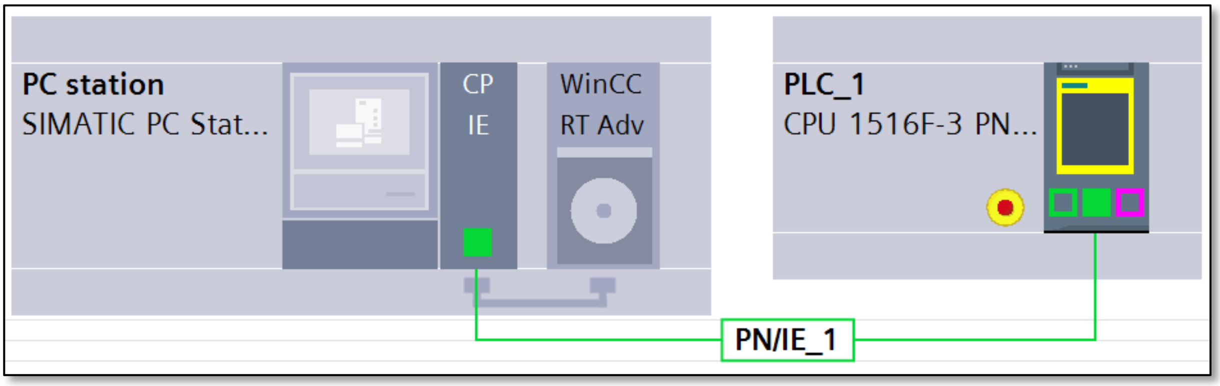


Figure III.3: *TIA Portal Device Configuration*

This PLC is simulated using the Siemens SIMATIC S7-PLCSIM software.

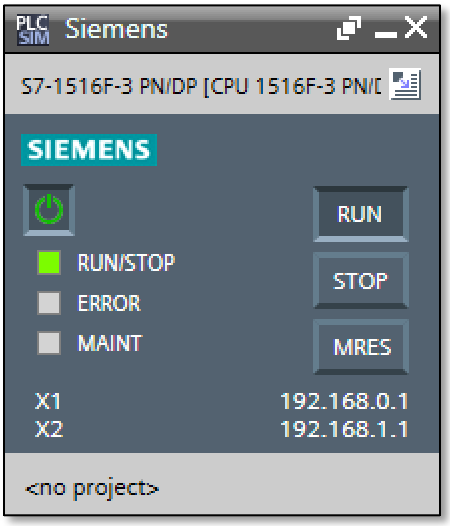


Figure III.4: *S7-PLCSIM Window*

III.2.2. Sequential Logic:

The PLC program was developed using 2 programming languages: LAD and SCL. The program was predominantly written in LAD language except for certain functions that required the flexibility of the SCL language. The program was split into several function blocks to organize it and facilitate the debugging phase.

Each zone has four operating modes:

- **Automatic:** in this mode, the pumping system equipment is actuated by the PLC. Pumps can be turned ON either remotely or locally.
- **Manual:** in this mode, the fire pumps are able to be actuated manually either remotely or locally.
- **Maintenance (No Flow):** this mode is designed for pumps and equipment maintenance in the absence of water (inlet valves are closed). In this mode, pumps can only be turned ON manually and locally.
- **Maintenance (Flow):** similarly to the no flow maintenance mode, this mode enables pump and equipment maintenance in the presence of water (inlet valves are open). The pumps can only be actuated manually and locally.

The table III.3 below indicates the state of the inlet and outlet valves in each operating mode:

Operating Mode	Discharge Valves	Feedback Valves	Water Tank Feed Valve
Automatic	Open	Open	Open
Manual	Open	Open	Open
Maintenance (No Flow)	Closed	Open	Closed
Maintenance (Flow)	Closed	Open	Open

Table III.3: *Fire Zones Operating Modes Valves State*

For clarity's sake, flowcharts were created to showcase the sequential logic of each part of the fire safety system, and they are organized by zone as follows:

- Well pumps logic
- Jockey pumps logic
- Fire pumps logic

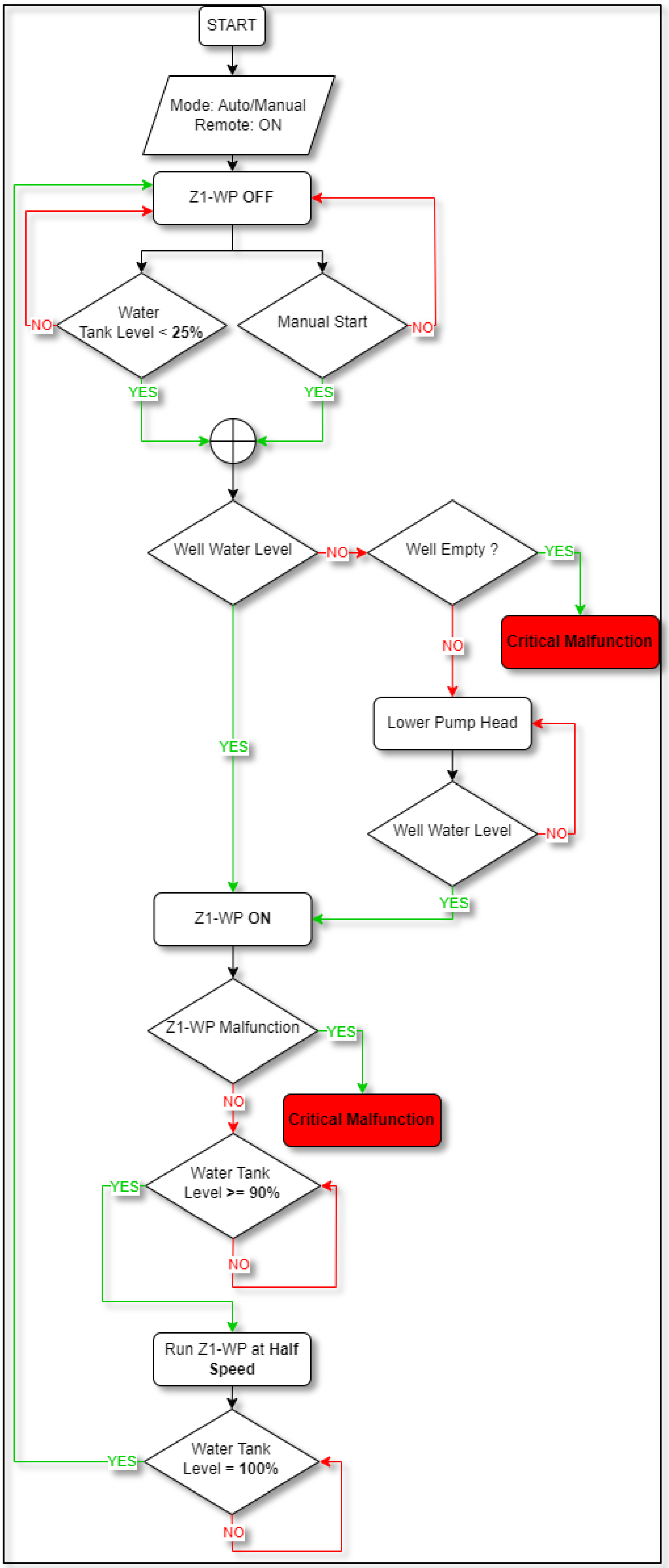


Figure III.5: *Administrative Zone Well Pump Operation*

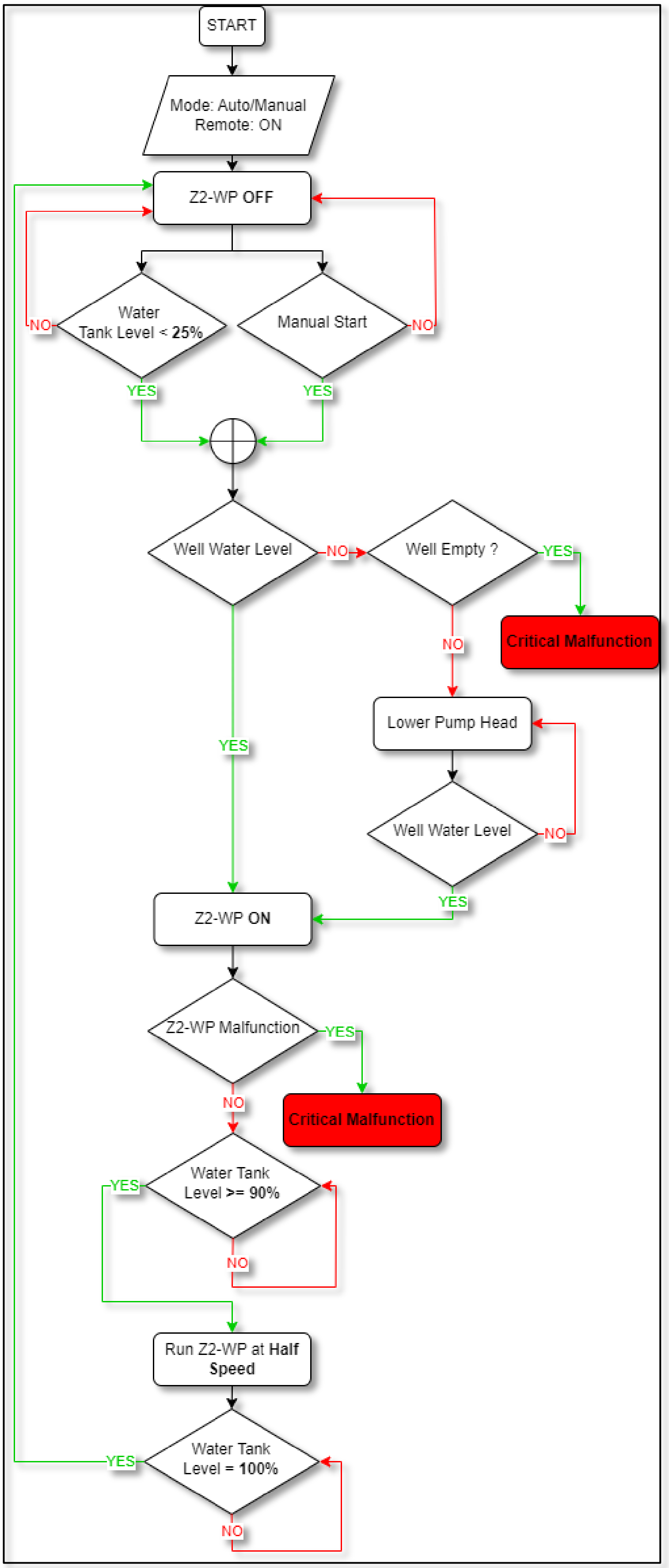
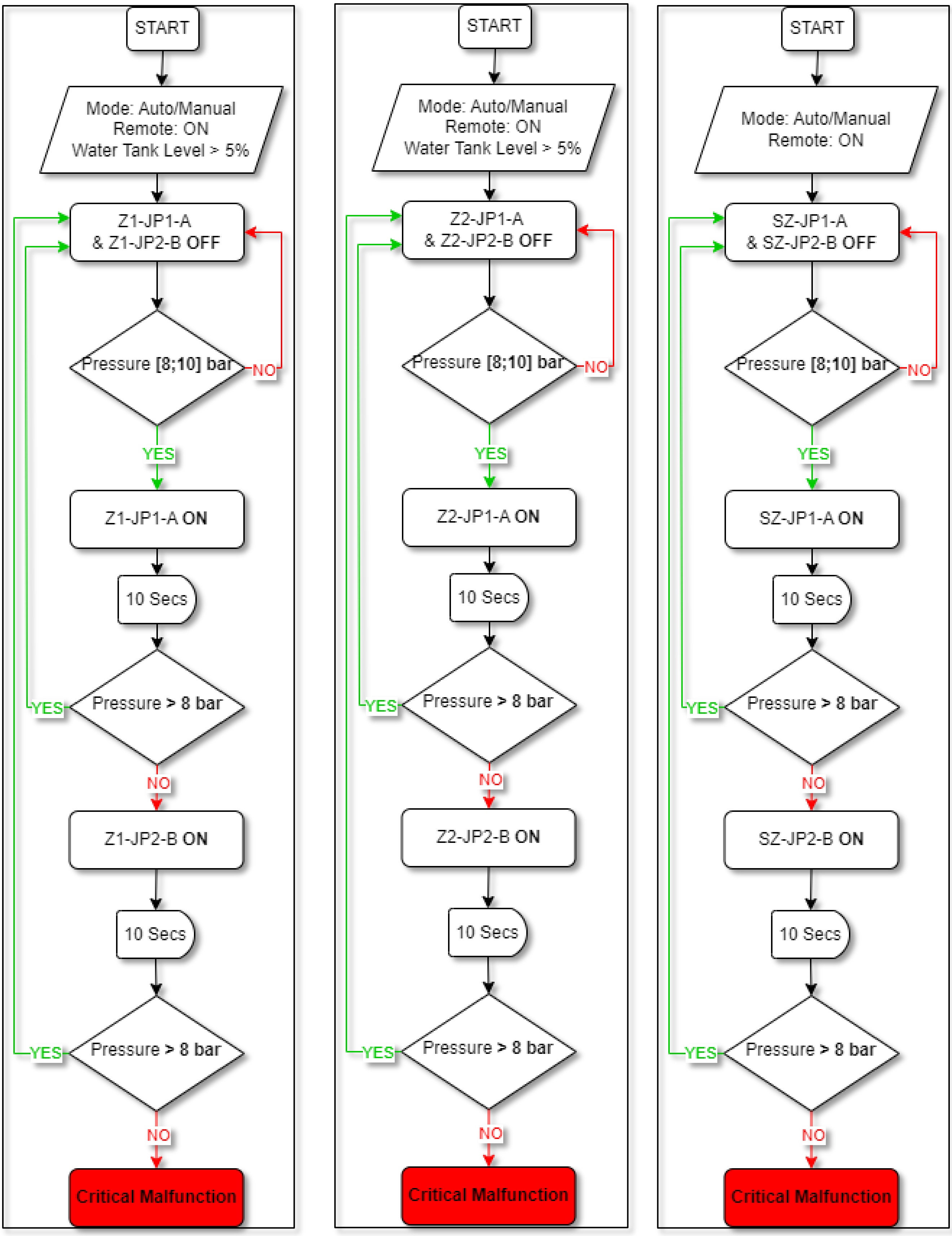


Figure III.6: *Industrial Zone Well Pump Operation*



(a) (b) (c)

Figure III.7: *Jockey Pumps Operation of the Administrative (a), Industrial (b) and Sea (c) Zones*

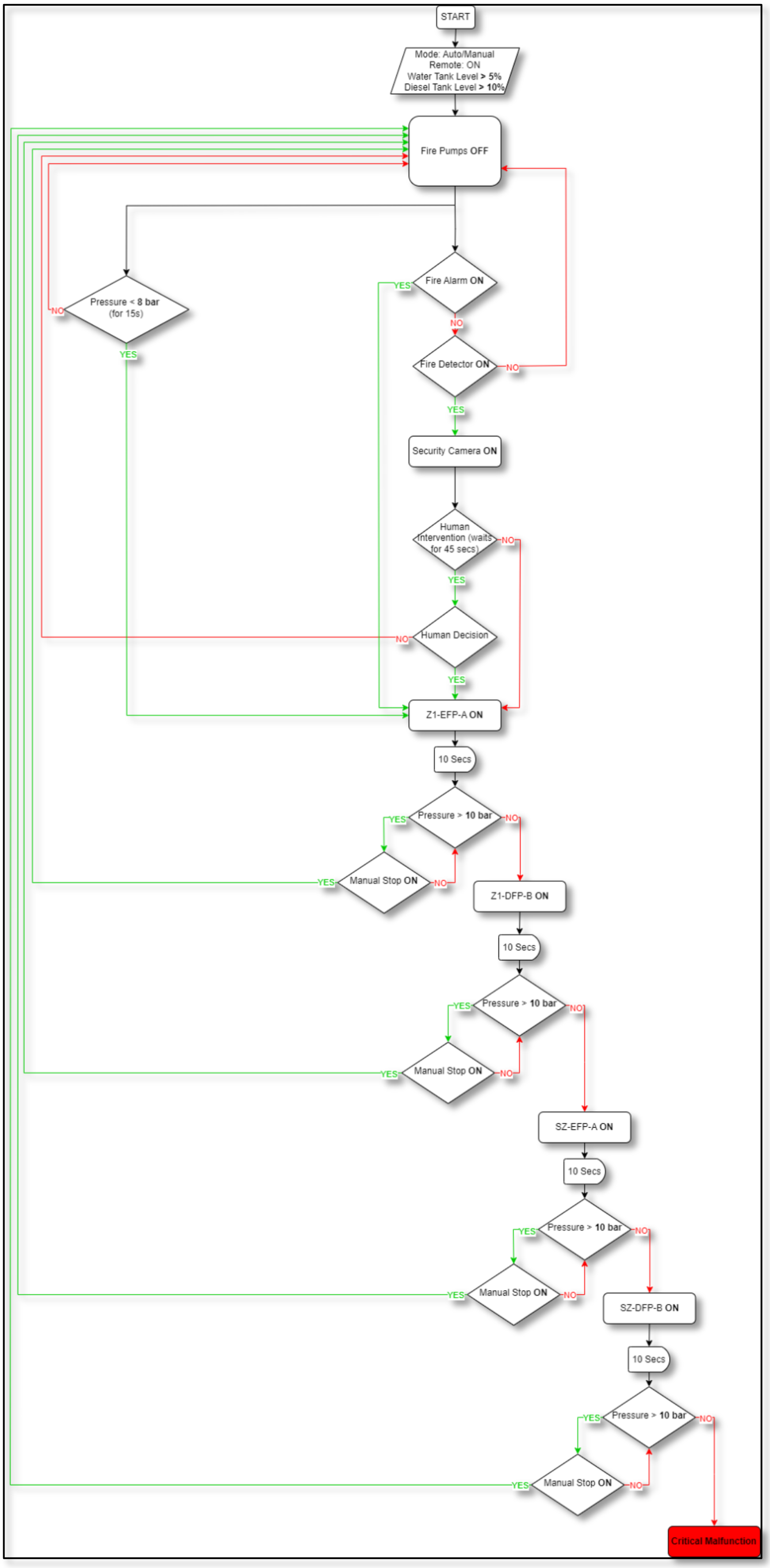


Figure III.8: Administrative Zone Alarm Fire Pumps Operation

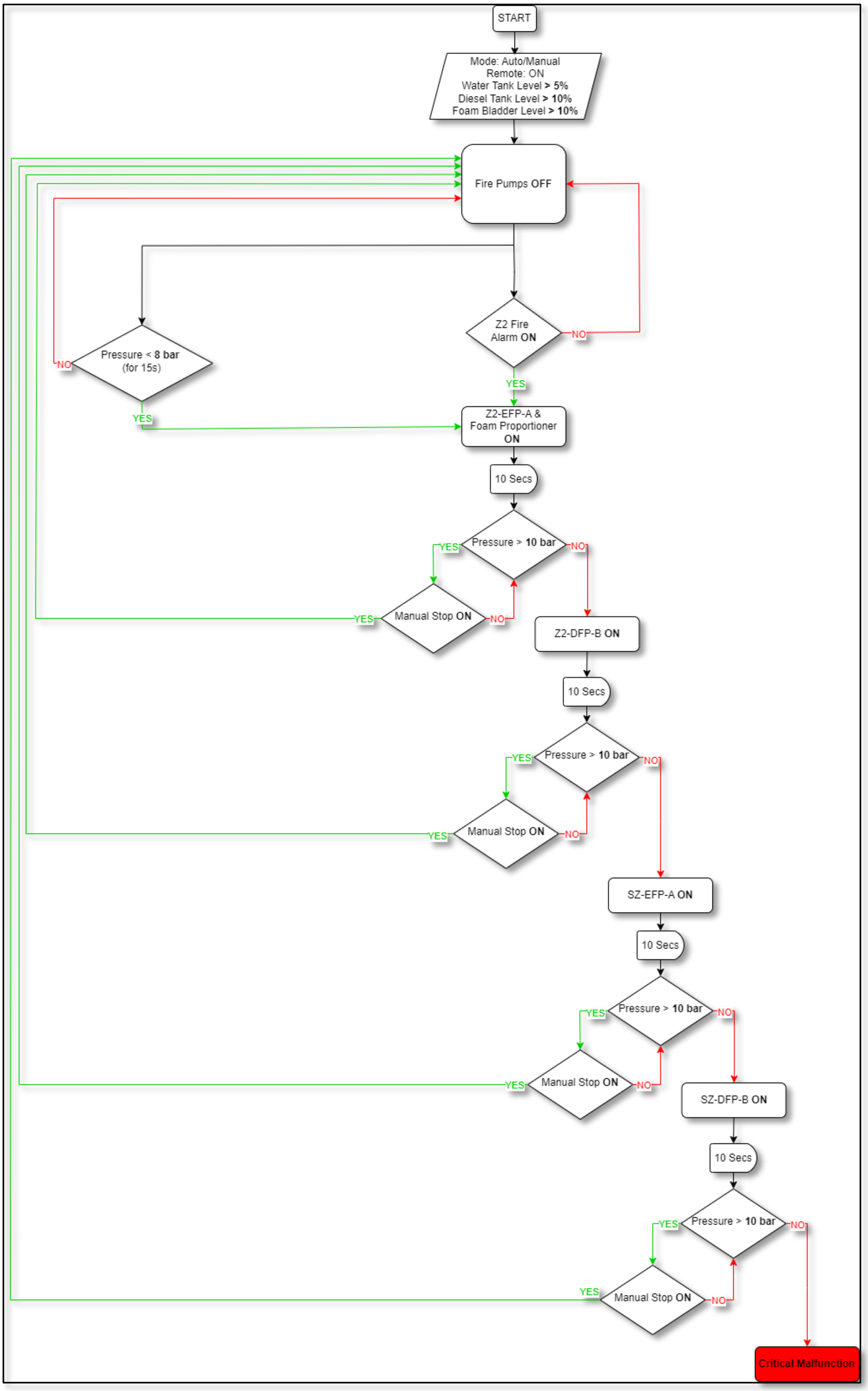


Figure III.9: *Industrial Zone Alarm Fire Pumps Operation*

In the critical event of a fire alarm in both the administrative and industrial zones, with a simultaneous failure of both electric and diesel fire pumps in those zones, both sea zones' fire pumps turn on with each pump providing support to one of the two affected zones (administrative or industrial).

- Deluge valves along with sprinklers are automatically activated when a fire in the pumping rooms is detected.
- All feedback valves are automatically closed when a fire alarm is triggered.
- Pressure relief valves in the industrial zone automatically open when the water pressure exceeds 12.1 bar.

In the event of a fire alarm being triggered on any floor other than the first floor, the elevator is automatically recalled to the first floor. This measure ensures that occupants can evacuate safely from the ground level. However, if the alarm is triggered on the first floor, the elevator is recalled to the second floor, enabling occupants to evacuate from an alternative level.

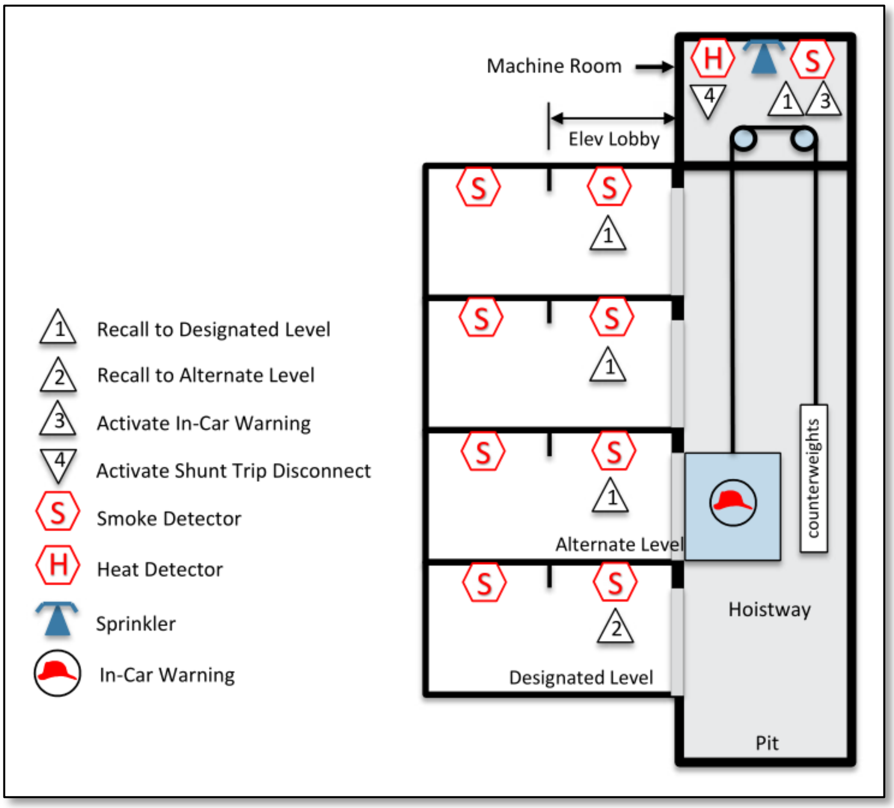


Figure III.10: *Elevator Emergency Recall Process* [27]

III.2.3. Fire Brigade SMS Notification:

An essential feature of this system is the automated transmission of an emergency SMS to the fire brigade providing the precise location address. This feature is activated when the fire alarm of any fire zone is triggered. This ensures a rapid response of the fire-fighting personnel minimizing the risk of fire escalation and potential catastrophic consequences. This solution is developed using a Node-Red flow. This flow requires the two additional packages shown in the figure III.11 below that can be installed from the pallete manager within the Node-Red flow screen.

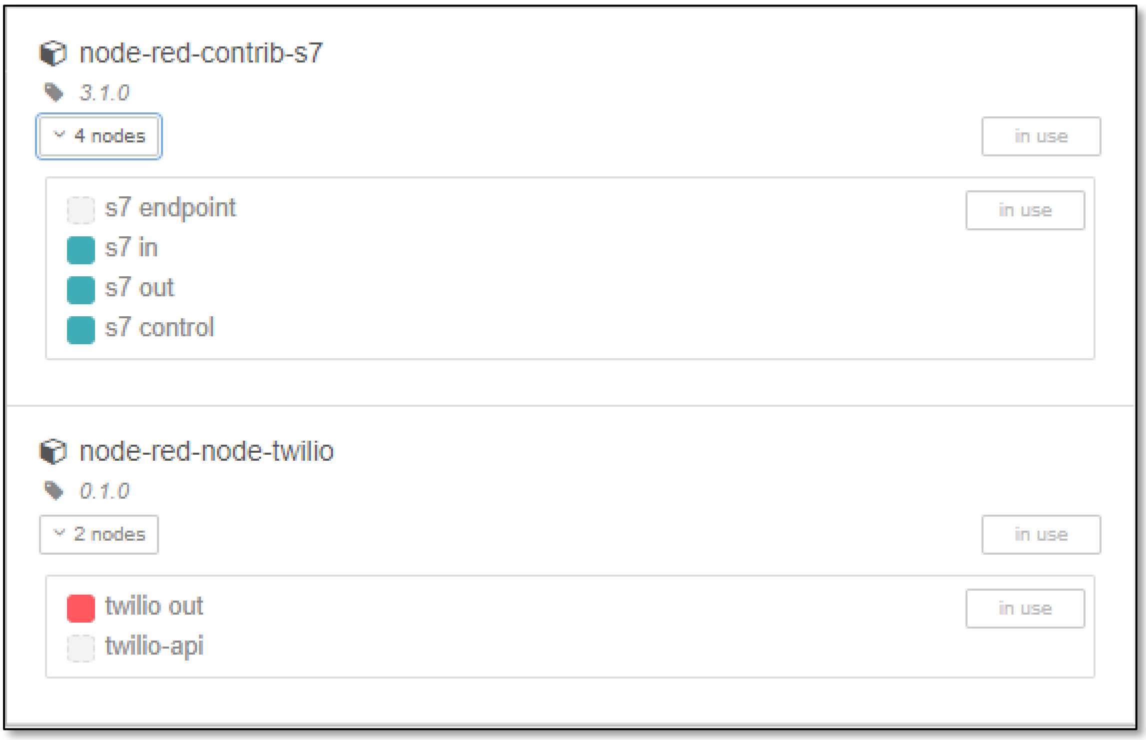


Figure III.11: *Node Red Required Add-ons*

The node-red-contrib-s7 add-on facilitates seamless integration between the simulated S7-1516F PLC and the Node-RED flow, enabling bidirectional communication and data exchange. While the node-red-node-twilio add-on enables the use of a mobile communication service called Twilio. This service provides users with a cost-free virtual mobile number, granting the ability to programmatically send SMS notifications to specified recipient numbers.

The node-red-contrib-s7 package requires an accessible online IP address for the PLC via the Ethernet TCP/IP protocol. This is achieved using the NetToPLCSIM software which facilitates the assignment of a virtual IP address from the local S7-PLCSIM address, therefore, rendering the PLC simulation accessible over the local network.

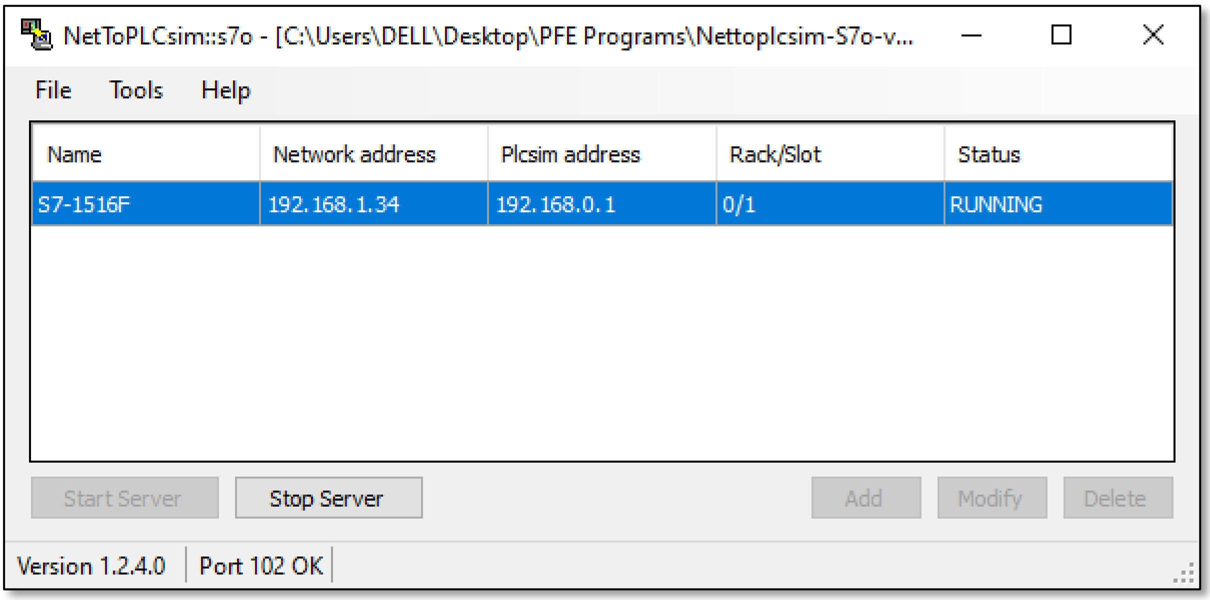


Figure III.12: *NetToPLCSIM Configuration*

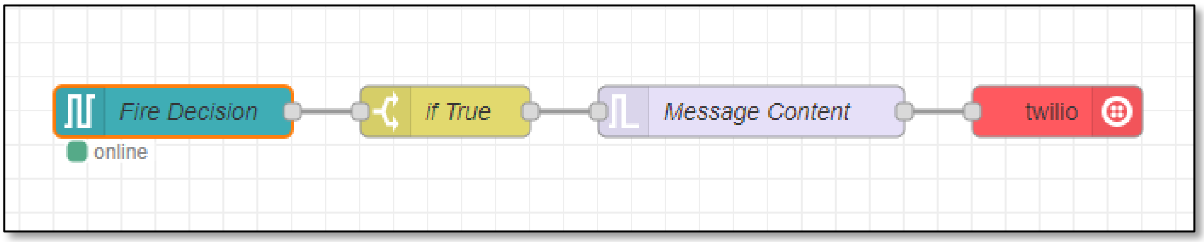


Figure III.13: *Node Red Flow*

- The "Fire Decision" node is an "s7 endpoint" node from the node-red-contrib-s7 add-on. This type of node continuously monitors the boolean state associated with the alarm conditions across all fire zones with a cycle time of 500 ms. In the variables tab, the address of the fire decision output from the PLC has to be specified. In this case, DB19 refers to the data block where the required variable is stored and X6888.6 is the bit offset of this variable i.e. its position within this data block.

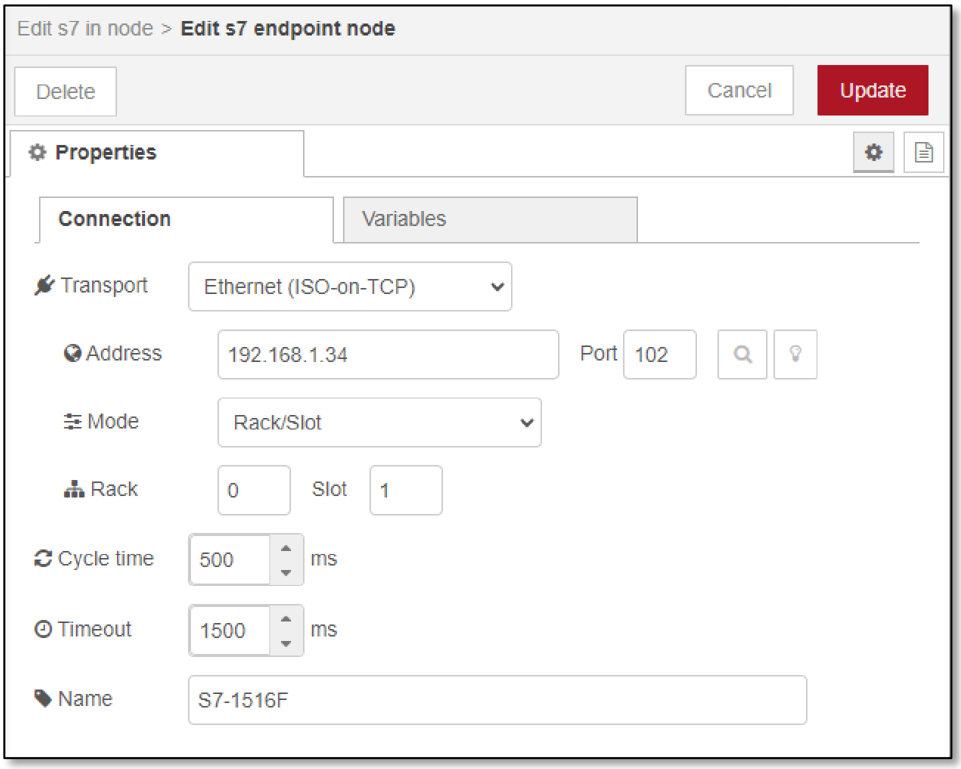


Figure III.14: *Node-Red Fire Decision Node Connection Configuration*

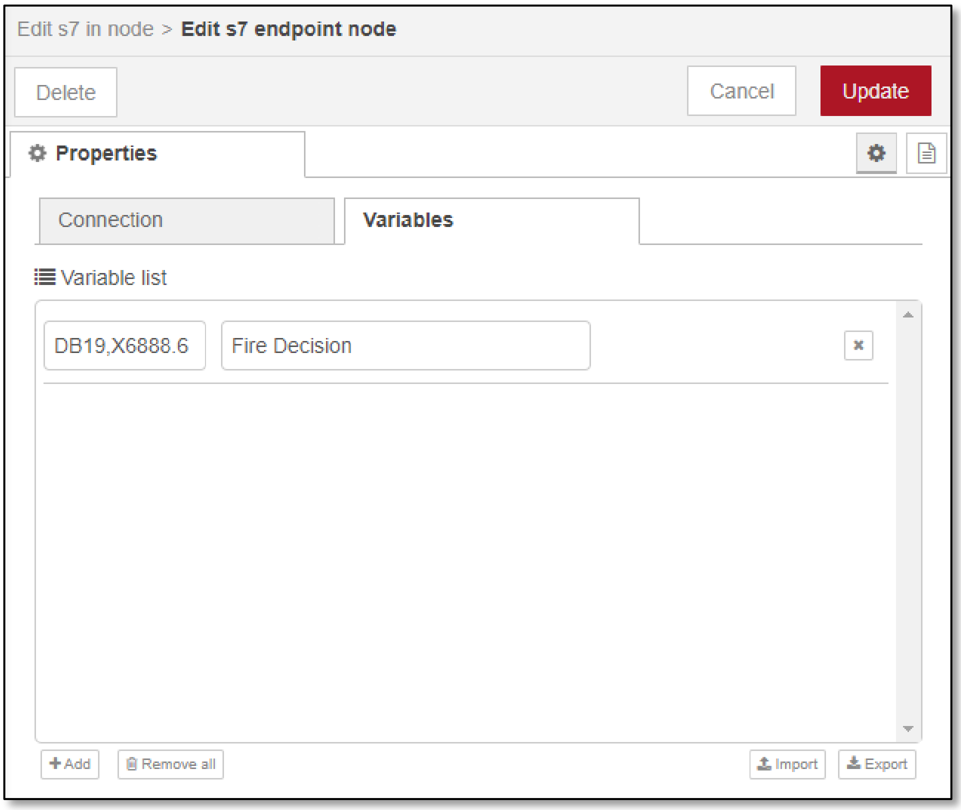


Figure III.15: *Node-Red Fire Decision Node Variable Configuration*

- The "if True" node is active only when the fire decision is activated (true).
- The "Message Content" node contains the SMS text.

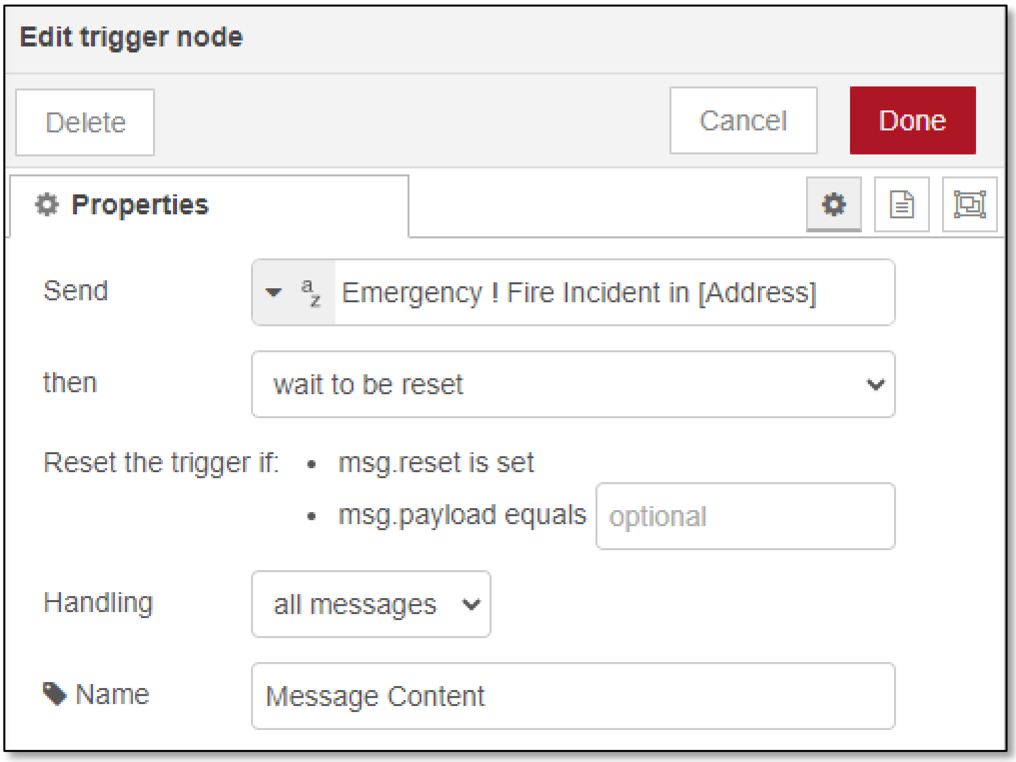


Figure III.16: *Node-Red Message Content Node Configuration*

- The "Twilio" node establishes the connection to the mobile communication service via their API by specifying a unique set of parameters provided to the user (account SID, phone number, and token). The recipient's mobile number has to also be specified within this node.

Figure III.17: *Node-Red Twilio Node Sender Configuration*

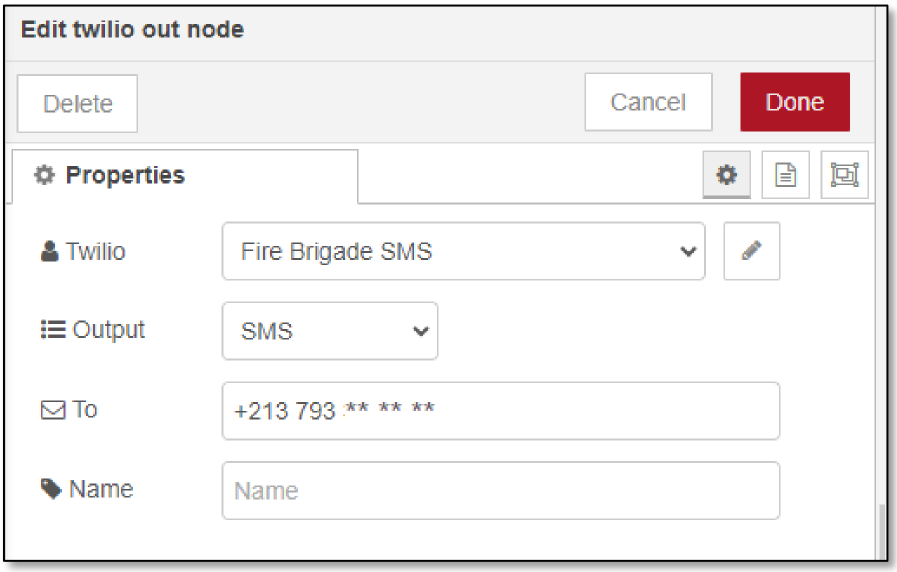


Figure III.18: *Node-Red Twilio Node Recipient Configuration*

Through this flow, when a fire alarm is triggered, the SMS message shown in the figure III.19 below is sent to the fire brigade.

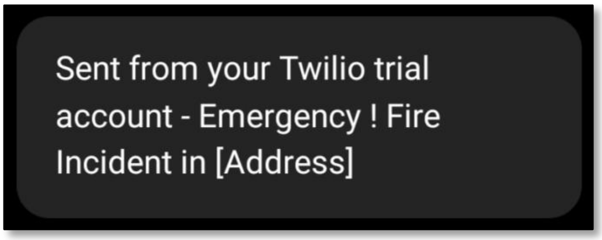


Figure III.19: *Fire Alarm SMS*

III.3. SCADA System:

The SCADA system was developed for a SIMATIC PC Station using WinCC RT Advanced and simulated on WinCC Runtime. The graphical user interface was tailored towards ease of access to the critical information at a glance with intuitive design and navigation. This was achieved using pop-up windows, sliding menus along with system alarms and warnings.

III.3.1. Home View:

The home view is the main screen. It provides access to all other views through the left hand side navigation bar. Each zone has an indicators area providing the user with the most important information at a glance. Each zone has a general state indicator at the bottom. The background color indicates the real-time state of the entire system.

- **Green:** There are no warnings, alarms or equipment failures.

Figure III.20: *SCADA Home View (Safe)*

- **Yellow:** There are warnings or equipment failures but no fire alarm are triggered.

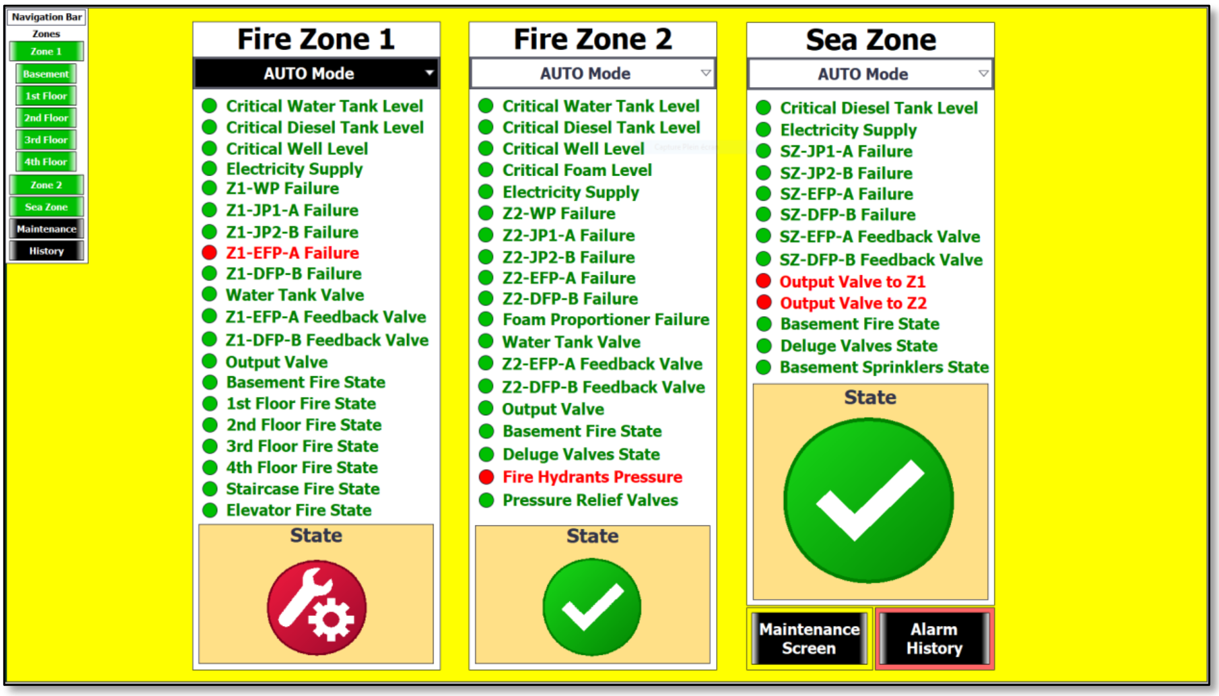


Figure III.21: SCADA Home View (Warning)

- **Orange:** The critical threshold of a fire detector is exceeded.

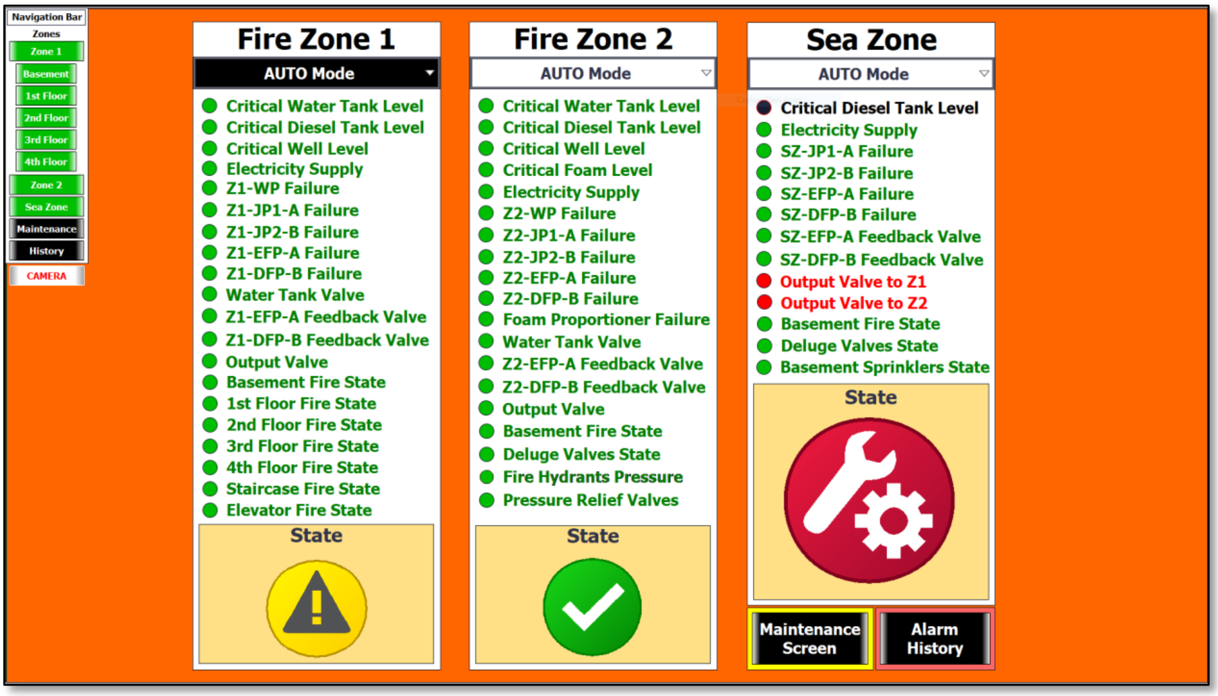


Figure III.22: SCADA Home View (Alert)

- **Red:** A fire alarm is triggered.

Figure III.23: *SCADA Home View (Alarm)*

During alert (orange) or alarm (red) situations, a camera button appears at the bottom of the navigation bar. Clicking it displays the live feed from the surveillance camera of the room where the fire detector was triggered. The surveillance camera personnel are able to activate the alarm or dismiss it. This allows for a visual confirmation of the potential fire threat allowing an early activation of the fire alarm.

Figure III.24: *SCADA Surveillance Camera View*

III.3.2. Administrative Fire Zone Pumping Station View:

In this view, the user has access to the following administrative fire zone's pumping station information:

- Well pump operating state, warnings and malfunctions.
- Administrative Fire zone operating mode selector.
- Water storage tank level and inlet pressure.
- Valves state indicators.
- Fire pumps and jockey pumps manual operation switch, functioning and failure states.
- Electric power supply and electric generator states.
- Diesel tank level.
- Commons discharge collector water pressure.
- Pumping station fire state.

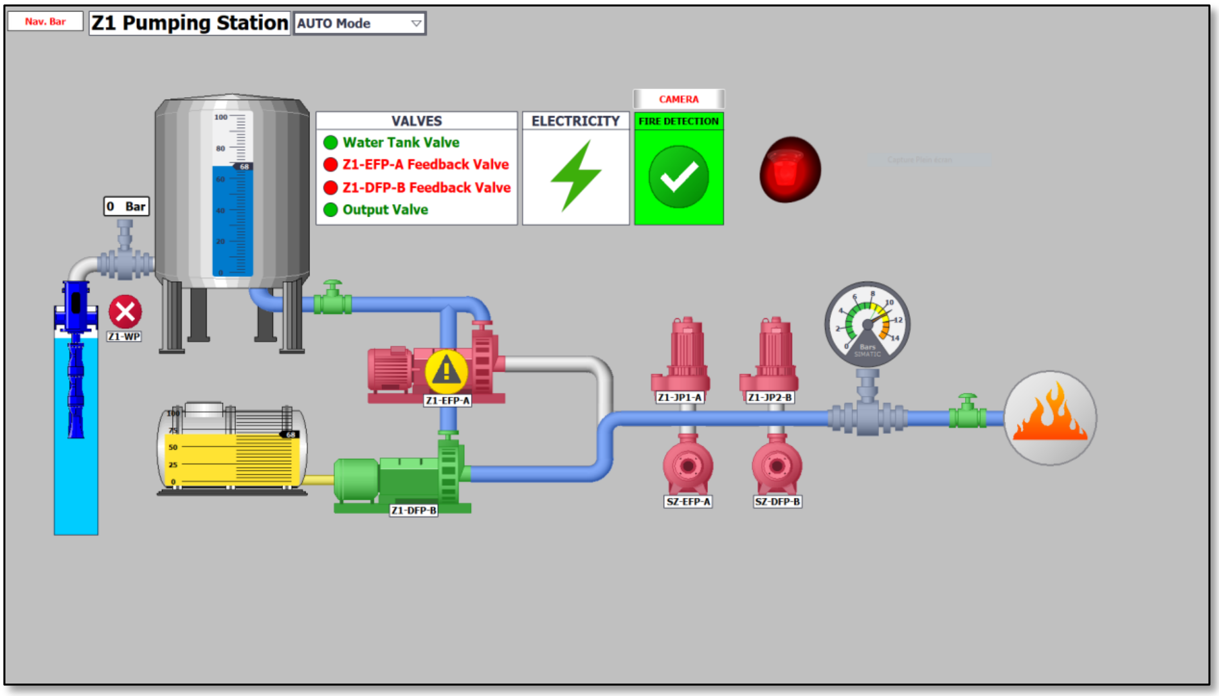


Figure III.25: *SCADA Administrative Fire Zone Pumping Station View*

III.3.3. Administrative Fire Zone Floors Detection Zones View:

Each floor has a view used to display the state and location of the fire alarm within the building layout. Additionally, the sprinkler activation state as well as the audiovisual notifications devices state for each room is displayed. All the four floors have the same layout. A colored background for each room is utilized to indicate the fire detector's state as follows:

- **Green:** The room is safe.
- **Yellow:** The fire detector exceeded the warning threshold which depends on each of the four fire sensors.
- **Orange:** The fire detector is triggered and the danger thresholds are exceeded. However, one of the four fire detection conditions is still not fulfilled (discussed in Chapter IV).
- **Red:** One of the four fire detection conditions is fulfilled indicating the presence of a fire incident.

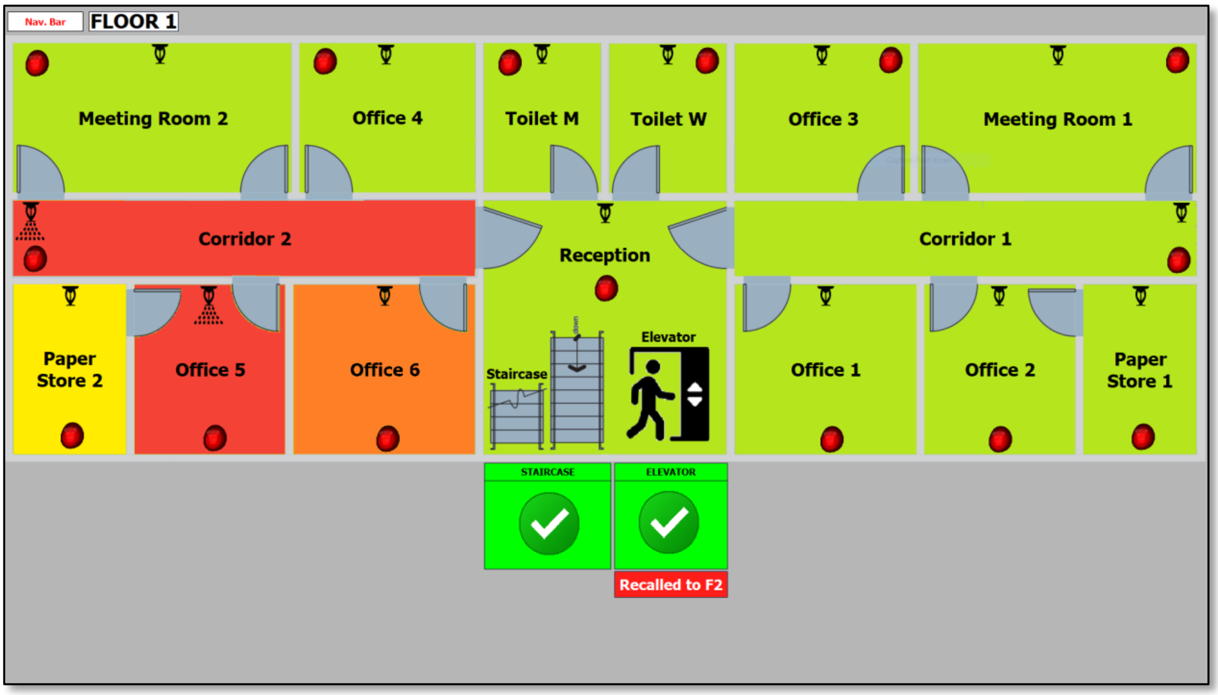


Figure III.26: *SCADA Administrative Zone 1st Floor Detection Zone View*

III.3.4. Industrial Fire Zone Pumping Station View:

In this view, the user has access to the following industrial fire zone's pumping station information:

- Well pump operating state, warnings and malfunctions.
- Industrial fire zone operating mode selector.
- Water storage tank level and inlet pressure.
- Valves state indicators.
- Pressure relief valves state indicators.
- Fire hydrants outlet water pressure.
- Fire pumps and jockey pumps manual operation switch, functioning and failure states.
- Electric power supply and electric generator states.
- Diesel tank level.
- Foam concentrate bladder level and valve.
- Foam proportioner operation state.
- Commons discharge collector water pressure.
- Pumping station fire state.

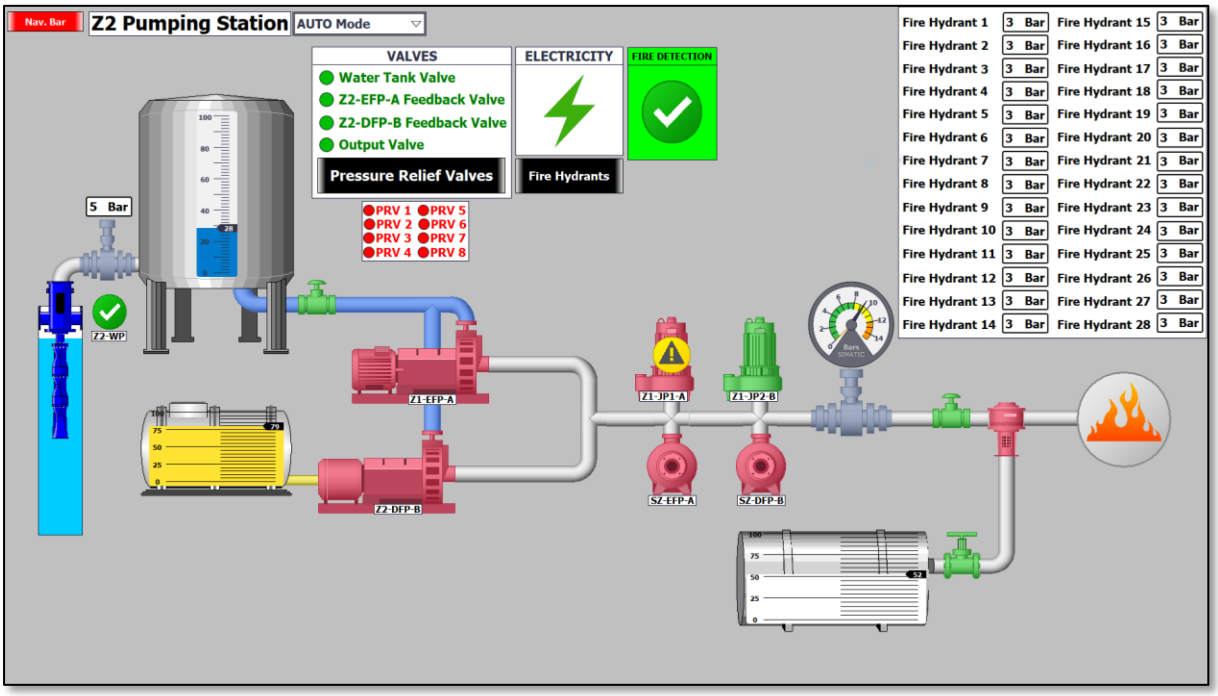


Figure III.27: *SCADA Industrial Fire Zone Pumping Station View*

III.3.5. Sea Fire Zone Pumping Station View:

In this view, the user has access to the following sea fire zone's pumping station information:

- Sea fire zone operating mode selector.
- Water storage tank level and inlet pressure.
- Valves state indicators.
- Pressure relief valves state indicators.
- Fire hydrants outlet water pressure.
- Fire pumps and jockey pumps manual operation switch, functioning and failure states.
- Electric power supply and electric generator states.
- Diesel tank level.
- Commons discharge collector water pressure.
- Pumping station fire state.

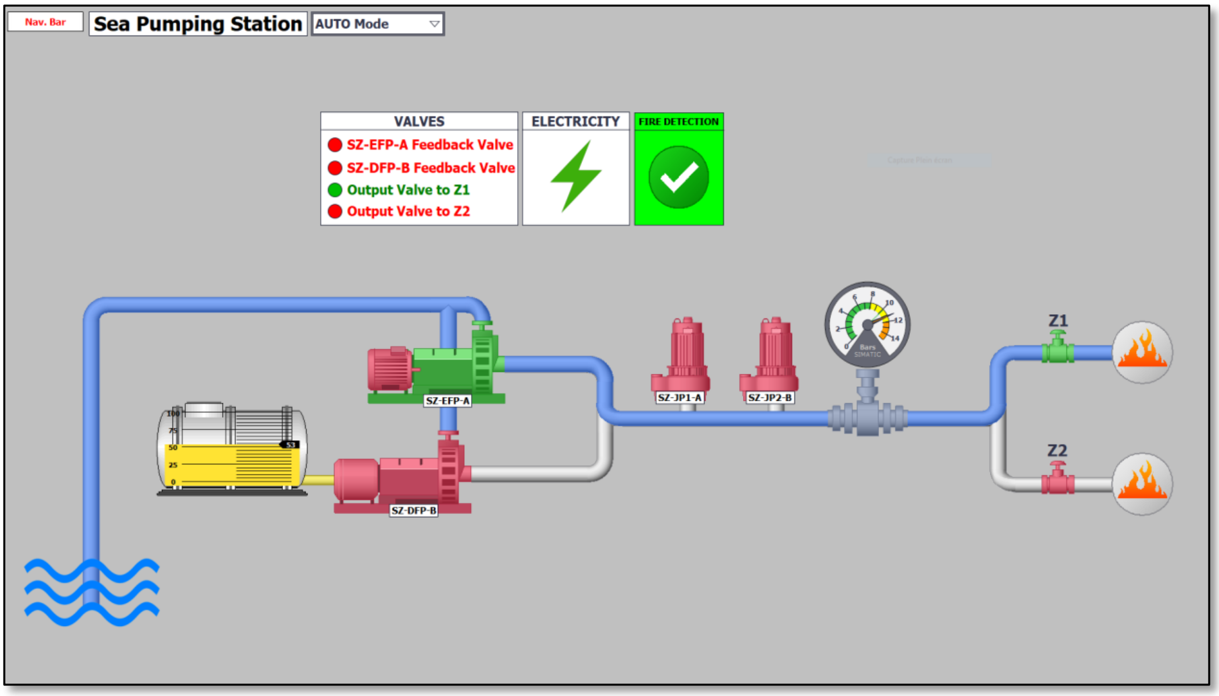
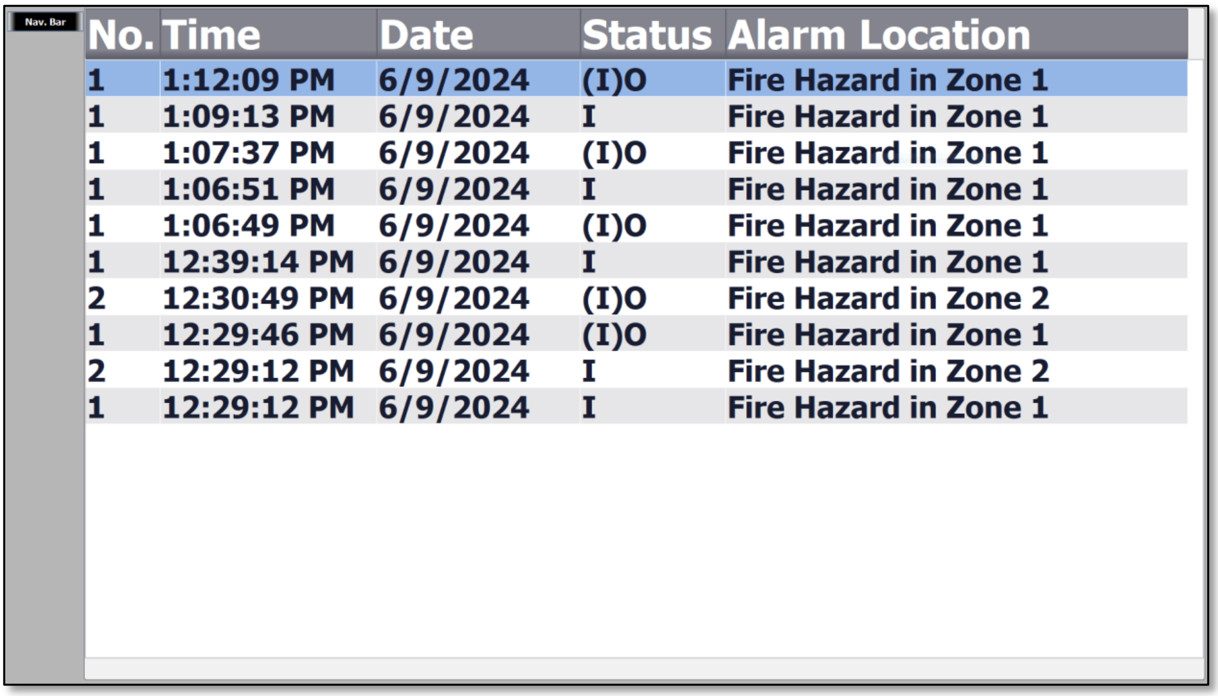


Figure III.28: *SCADA Sea Zone Pumping Station View*

III.3.6. Alarms History View:

The alarms history view on the SCADA control interface provides the time, date, status and location of the fire alarm for each zone.



No.	Time	Date	Status	Alarm Location
1	1:12:09 PM	6/9/2024	(I)O	Fire Hazard in Zone 1
1	1:09:13 PM	6/9/2024	I	Fire Hazard in Zone 1
1	1:07:37 PM	6/9/2024	(I)O	Fire Hazard in Zone 1
1	1:06:51 PM	6/9/2024	I	Fire Hazard in Zone 1
1	1:06:49 PM	6/9/2024	(I)O	Fire Hazard in Zone 1
1	12:39:14 PM	6/9/2024	I	Fire Hazard in Zone 1
2	12:30:49 PM	6/9/2024	(I)O	Fire Hazard in Zone 2
1	12:29:46 PM	6/9/2024	(I)O	Fire Hazard in Zone 1
2	12:29:12 PM	6/9/2024	I	Fire Hazard in Zone 2
1	12:29:12 PM	6/9/2024	I	Fire Hazard in Zone 1

Figure III.29: *SCADA Alarms History View*

III.3.7. Maintenance Schedule View:

This view provides the field technicians with a tool to schedule inspection, testing and maintenance operations for the system’s equipment. It functions as maintenance agenda that registers the most recent inspection, testing and maintenance dates by pressing the “Done” button then computes the date of the next scheduled operation according to the NFPA 72 standard schedules. This efficient and organized approach ensures that all critical maintenance tasks are performed in time, minimizing downtime and maximizing the system's reliability and performance.

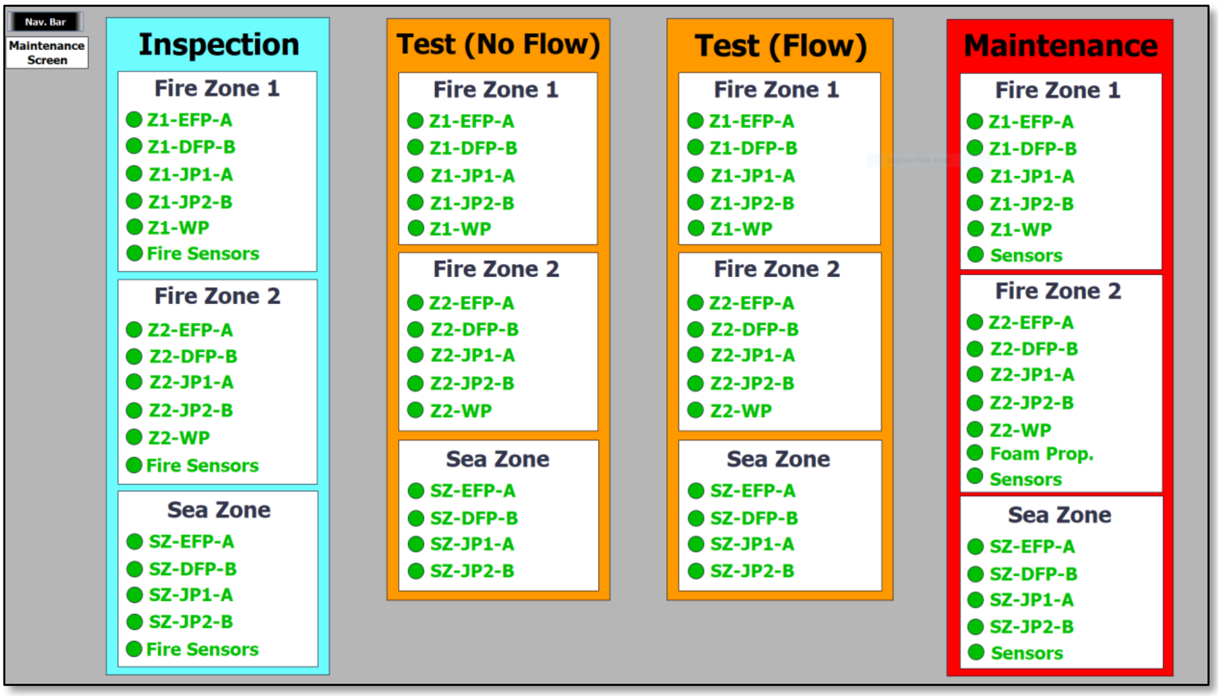


Figure III.30: *SCADA Maintenance Schedule View*

Equipment	Inspection	Test (No Flow)	Test (Flow)	Maintenance
Jockey Pumps	Weekly	Weekly	Annually	Annually
Electric Fire Pumps	Weekly	Weekly	Annually	Annually
Diesel Fire Pumps	Weekly	Weekly	Annually	Annually
Well Pumps	Weekly	Weekly	Annually	Annually
Foam Proportioner	/	/	/	Annually
Fire Sensors	Semi-Annually	/	/	/
Measurement Sensors	/	/	/	Annually

Table III.4: *Equipment Inspection, Test and Maintenance Schedules* [28]

III.4. Conclusion:

This chapter provided a thorough exploration of the automation and supervision solution developed for the fire-fighting system. Detailed insights were presented on the PLC configuration, control logic implementation using flowcharts, automated SMS notification, and the comprehensive SCADA system with real-time monitoring and alarm management.

- CHAPTER IV -

Fire Detection Algorithm

IV.1. Introduction:

This chapter introduces the core of the thesis: a fire detection algorithm utilizing fuzzy logic. This chapter provides a comprehensive understanding of the fire detection algorithm, its development, and its validation process. We justify the choice of fuzzy logic and explain the designed FIS for fire detection. We'll explore its type, inputs with their membership functions, the rule base, and the classification output. Furthermore, the integration of this FIS with the automation part of the project is discussed along with the fire alarm decision conditions. Preprocessing techniques like normalization and scaling are explained to ensure compatibility with real-world sensor data. Finally, the chapter details the FIS performance assessment using the FDS for simulated fire scenarios. System validation follows, evaluating detection rate, false alarm rates, and accuracy results.

IV.2. Fire Detection Algorithm:

The purpose is to design an accurate fire detector that combines the properties of several commercially available detectors. The fuzzy logic approach, especially when applied to a multi-sensor system, has the potential to outperform classical techniques. Therefore, fuzzy logic was the most suitable method to design this fire detector. Instead of relying on binary on/off thresholds, fuzzy logic employs rule-based decision-making allowing dynamic adjustments in response to the evolving environmental conditions within the monitored area. As a consequence, the system exhibits enhanced responsiveness by adapting its actions to the specific characteristics of a developing fire scenario. Fuzzy logic’s ability to model complex relationships and incorporate multi-sensor data reduces the likelihood of false alarms, enabling the system to differentiate between actual fire events and harmless environmental fluctuations. This project’s fire detection algorithm is developed using the MATLAB Fuzzy Logic Designer Toolbox and deployed in every room of the administrative fire zone building.

IV.2.1. Fuzzy Inference System (FIS):

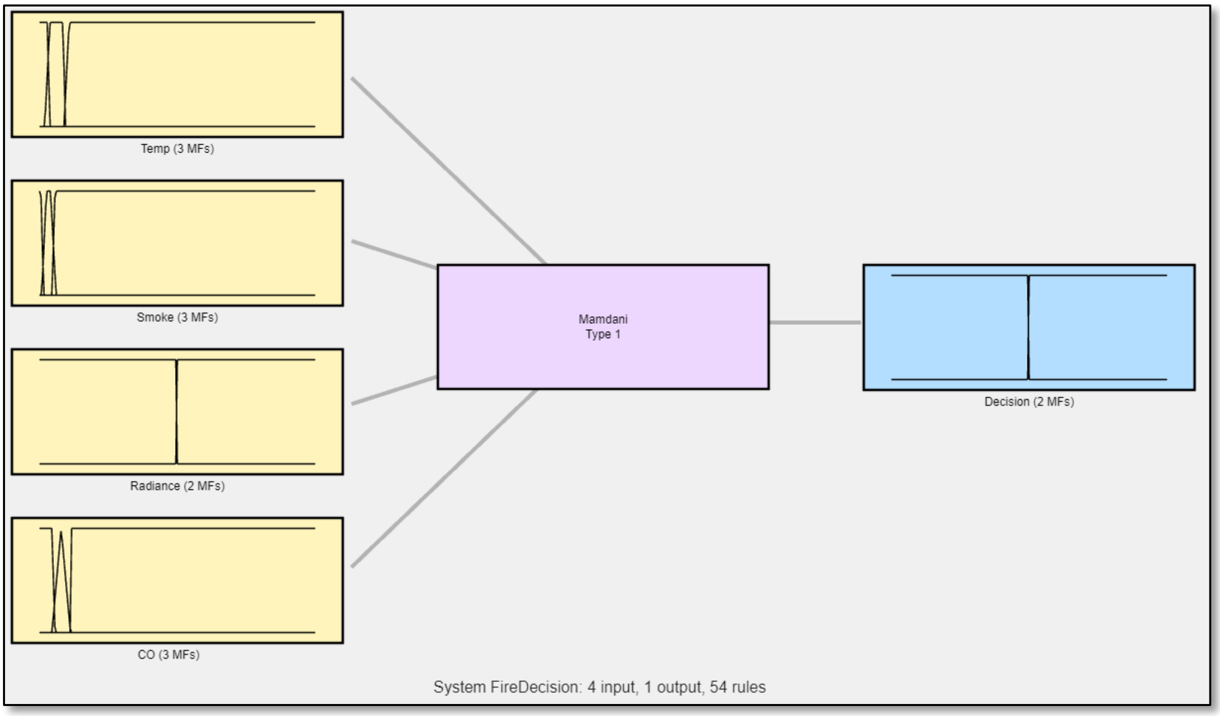


Figure IV.1: *Fire Detection FIS Overview*

The Fire detection fuzzy controller is a 4-input 1-output type-1 Mamdani FIS. The choice of the Mamdani variant was decided due to the nature of the fire decision output which requires a membership function. The FIS properties are shown in the figure IV.2 below.

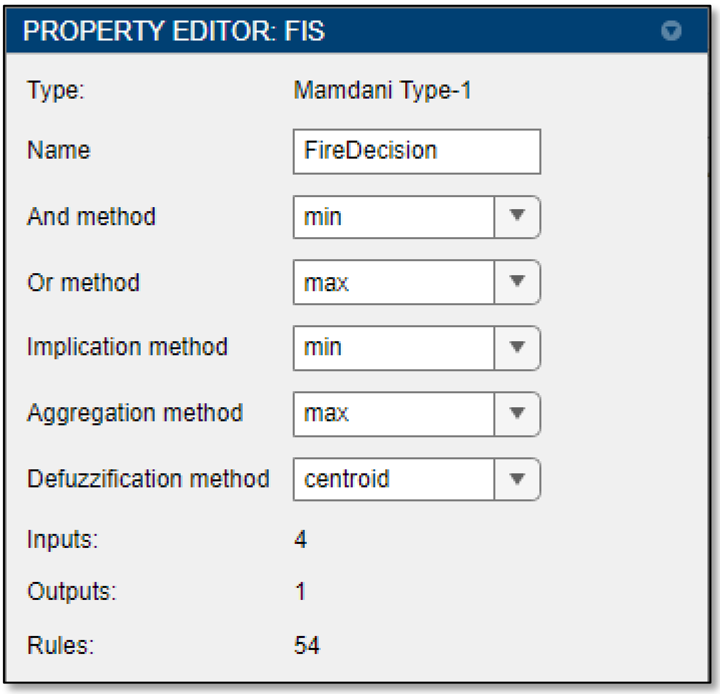


Figure IV.2: *Fire Detection FIS Properties*

IV.2.1.1. FIS Inputs:

The FIS inputs represent the four fundamental elements of fire, namely: temperature, smoke concentration, flame radiance and carbon monoxide concentration. These elements provide a highly accurate assessment of the fire severity while simultaneously minimizing false alarm rates. Each of these inputs is subsequently discussed in greater detail.

Temperature:

Temperature is measured in °C. The figures below display the input properties with the membership functions of the temperature sensor data.

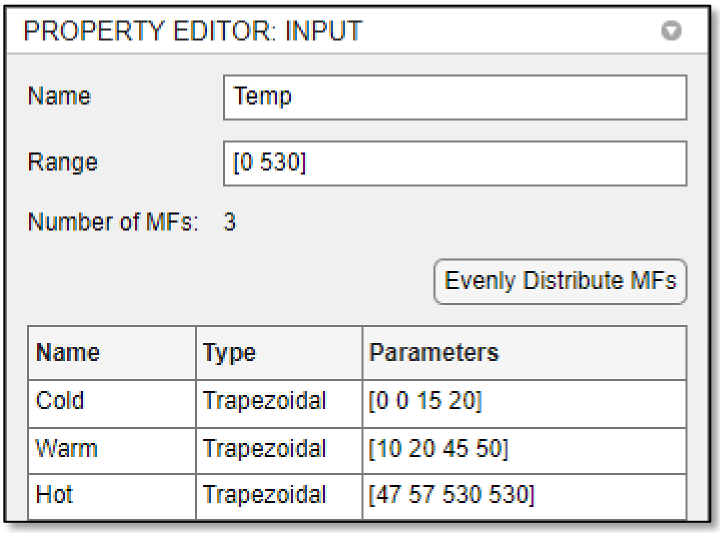


Figure IV.3: *FIS Temperature Input Properties*

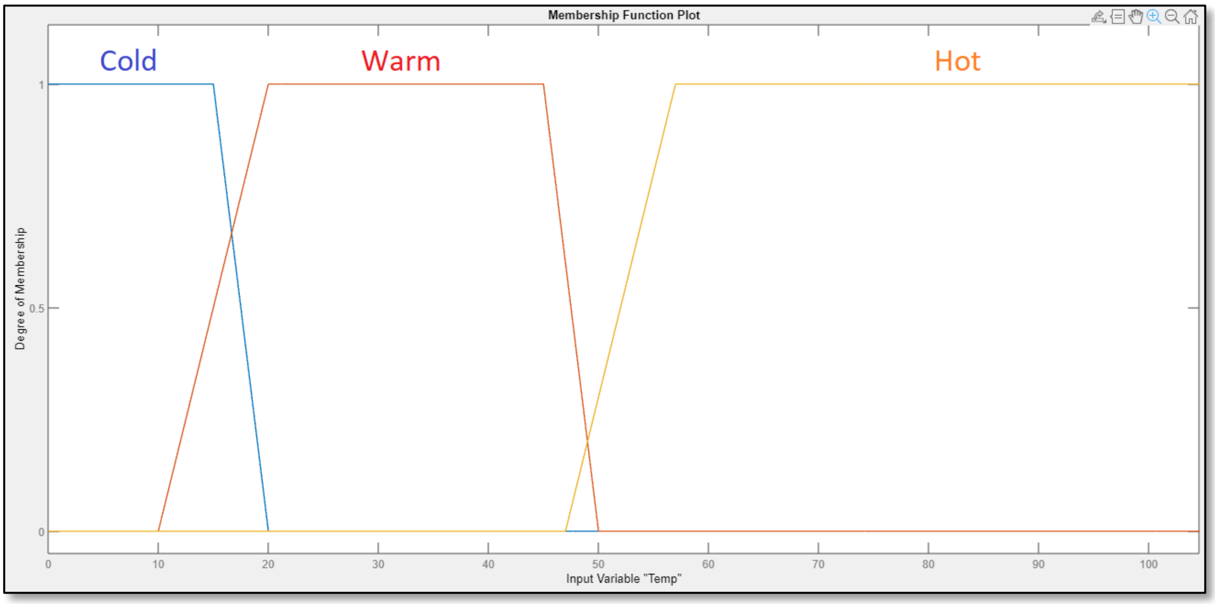
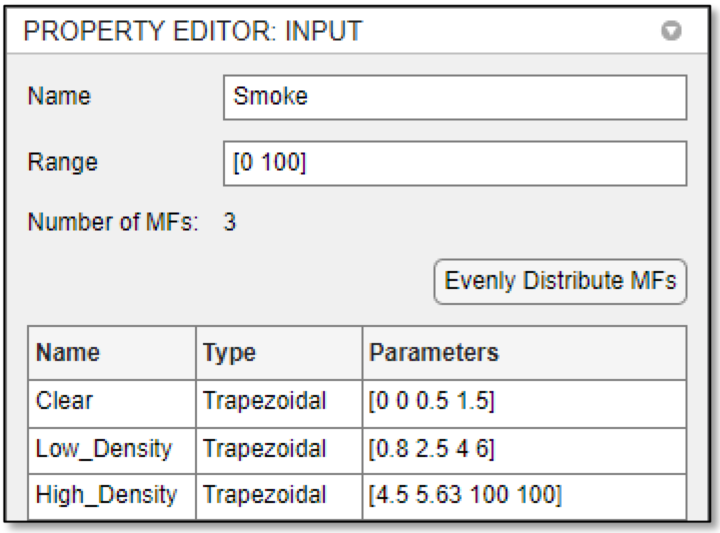


Figure IV.4: *Temperature Membership Functions Plot*

Smoke Obscuration Rate:

Smoke obscuration rate is measured in %/m. This unit represents the percentage of light blocked per meter of path length by the smoke. In other words, a higher percentage signifies greater light attenuation, meaning the smoke is denser and blocks more light. The figures below display the input properties with the membership functions of the smoke sensor data.


PROPERTY EDITOR: INPUT

Name: Smoke

Range: [0 100]

Number of MFs: 3

Evenly Distribute MFs

Name	Type	Parameters
Clear	Trapezoidal	[0 0 0.5 1.5]
Low_Density	Trapezoidal	[0.8 2.5 4 6]
High_Density	Trapezoidal	[4.5 5.63 100 100]

Figure IV.5: *FIS Smoke Obscuration Rate Input Properties*

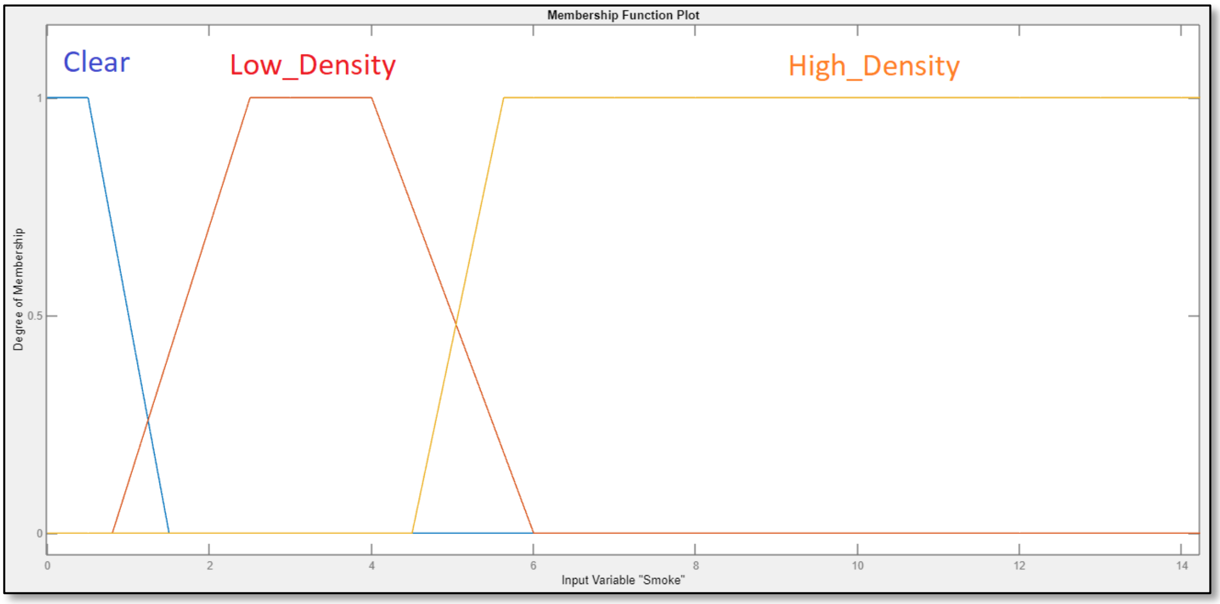


Figure IV.6: *Smoke Obscuration Rate Membership Functions Plot*

Flame Radiance:

Flame radiance is measured in kW/m2/sr. This unit quantifies the amount of radiant energy emitted per unit area of a flame per unit solid angle. It essentially describes the intensity of the flame's radiant heat transfer. It is commonly used as a measurement unit for infrared flame detectors. Due to the discrete nature of flame radiance, the linear S and Z shaped saturation functions are utilized as membership functions. The figures below display the input properties with the membership functions of the flame radiance data.

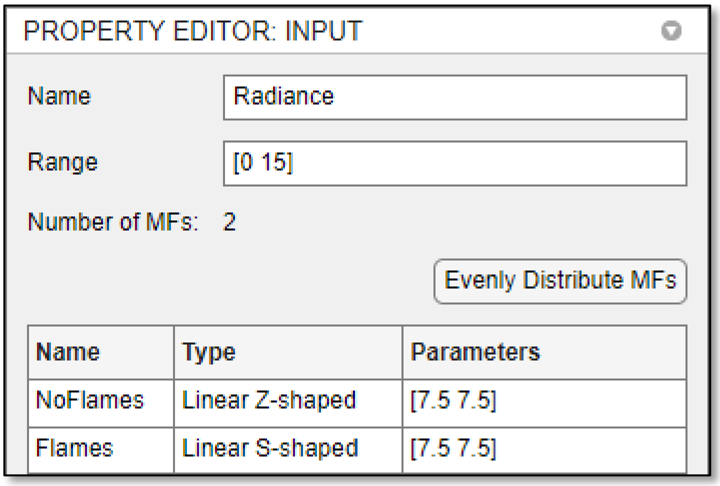


Figure IV.7: *FIS Flame Radiance Input Properties*

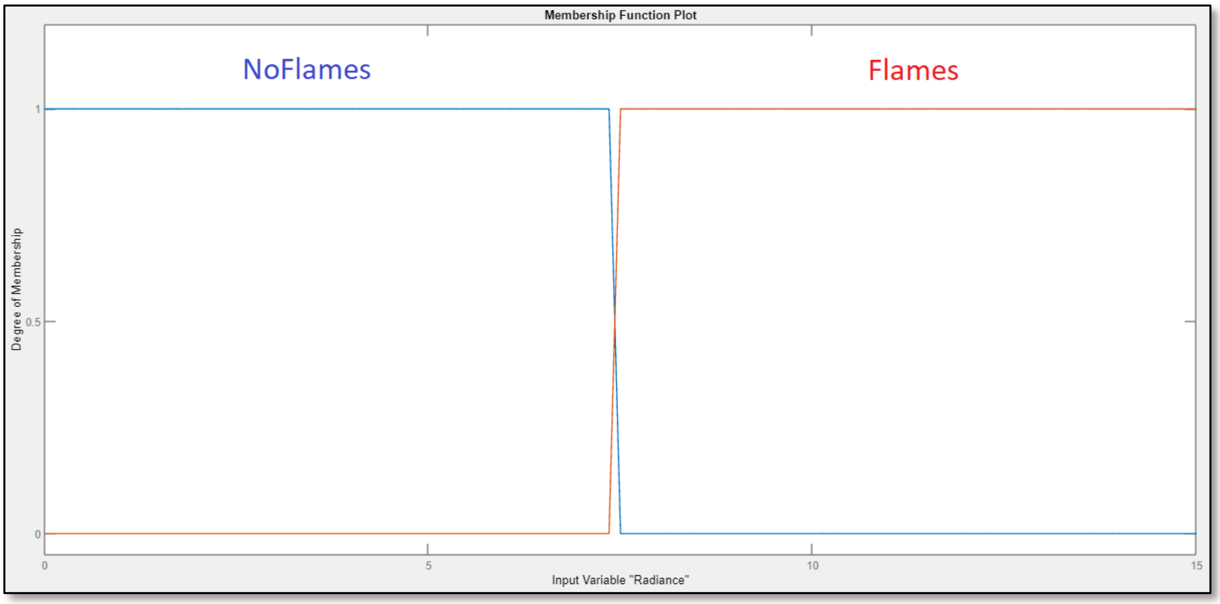


Figure IV.8: *Flame Radiance Membership Functions Plot*

CO Concentration:

While smoke and heat are often the first signs associated with fires, carbon monoxide (CO) detectors play a crucial role in fire detection since CO detectors can sense CO concentration levels even before smoke or significant heat is produced. Furthermore, certain types of fires might not produce significant smoke initially but can produce CO due to an incomplete combustion. A relatively high CO concentration in a closed room represents a life threat to occupants. Carbon monoxide concentration is measured in PPM. This unit indicates the number of CO molecules present in every million molecules of air. The relevant levels of CO concentration are listed in the table IV.1 below.

CO Concentration	Exposure Limit
50 ppm	Physical Symptoms after 8 hours
200 ppm	Physical Symptoms after 2-3 hours
400 ppm	Fatal after 3 hours
800 ppm	Fatal after 2-3 hours
1600 ppm	Fatal after 1 hour

Table IV.1: *Carbon Monoxide Centration Levels* [29]

The figures below display the input properties with the membership functions of the CO concentration data.

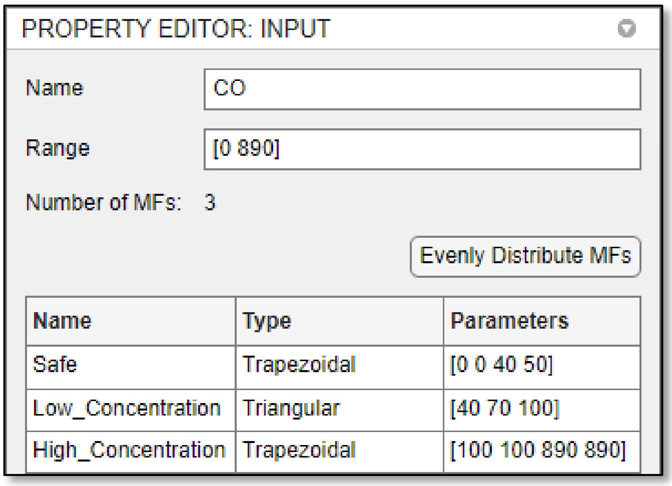


Figure IV.9: *FIS CO Concentration Input Properties*

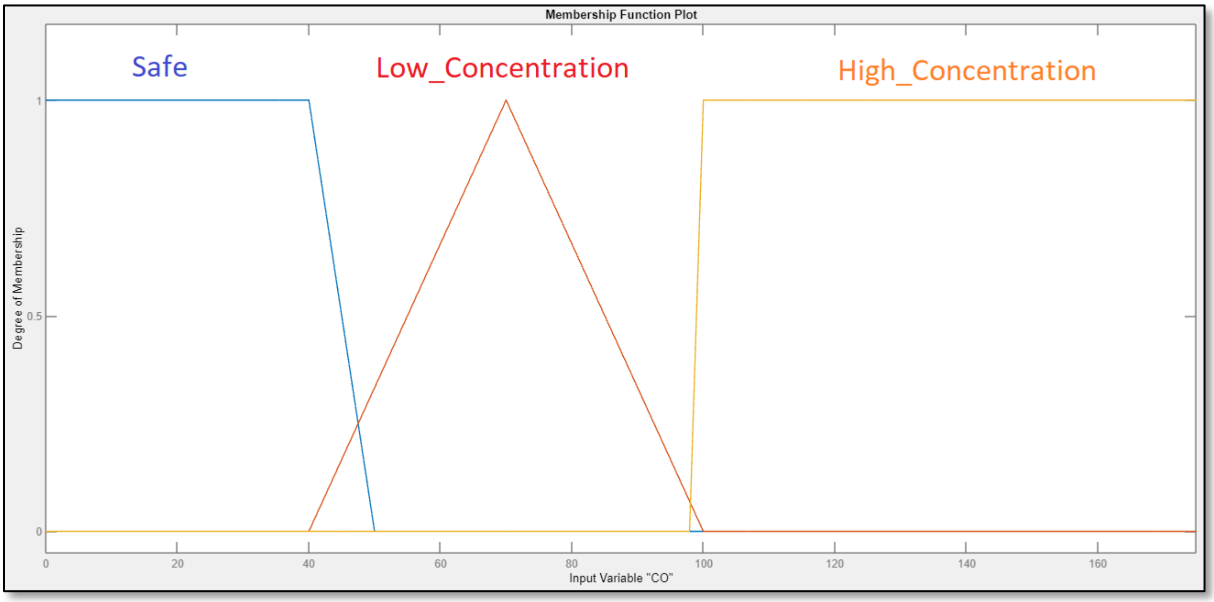


Figure IV.10: *CO Concentration Membership Functions Plot*

IV.2.1.2. Rule Base:

The fuzzy inference system employs a rule base consisting of 54 individual rules. These rules are designed to consider the combined data from all four sensors. Each rule carries a weight of unity, signifying equal influence in the decision-making process. A detailed listing of all 54 rules is provided in Appendix B for further reference.

Rule	Weight
If Temp is Cold and Smoke is Clear and Radiance is NoFlames and CO is Safe then Decision is Safe	1
If Temp is Warm and Smoke is Low_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1
If Temp is Hot and Smoke is High_Density and Radiance is Flames and CO is Low_Concentration then Decision is Alarm	1
If Temp is Hot and Smoke is High_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1

Figure IV.11: *FIS Rules Sample*

IV.2.1.3. FIS Output:

This fire detection system provides a binary fire classification with an output of: "0" signifying no fire detected and "1" indicating the presence of fire. This type of output is possible when utilizing the centroid defuzzification method. The crisp binary values are achieved thanks to the use of the linear S and Z-shaped saturation membership functions. The following figures illustrate the FIS output properties alongside the associated membership functions.

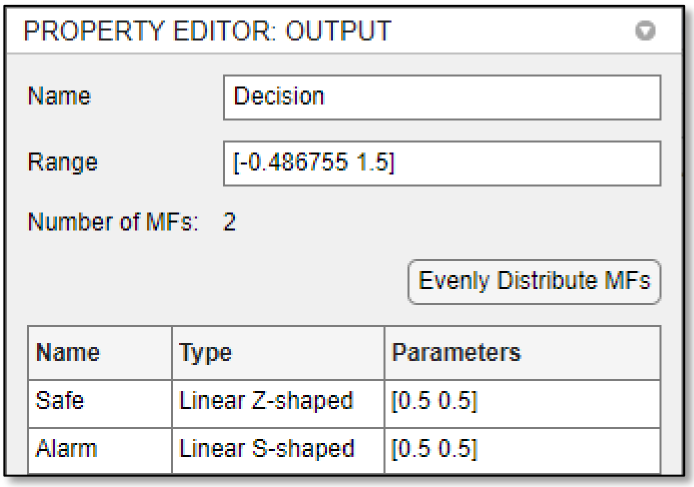


Figure IV.12: *FIS Output Properties*

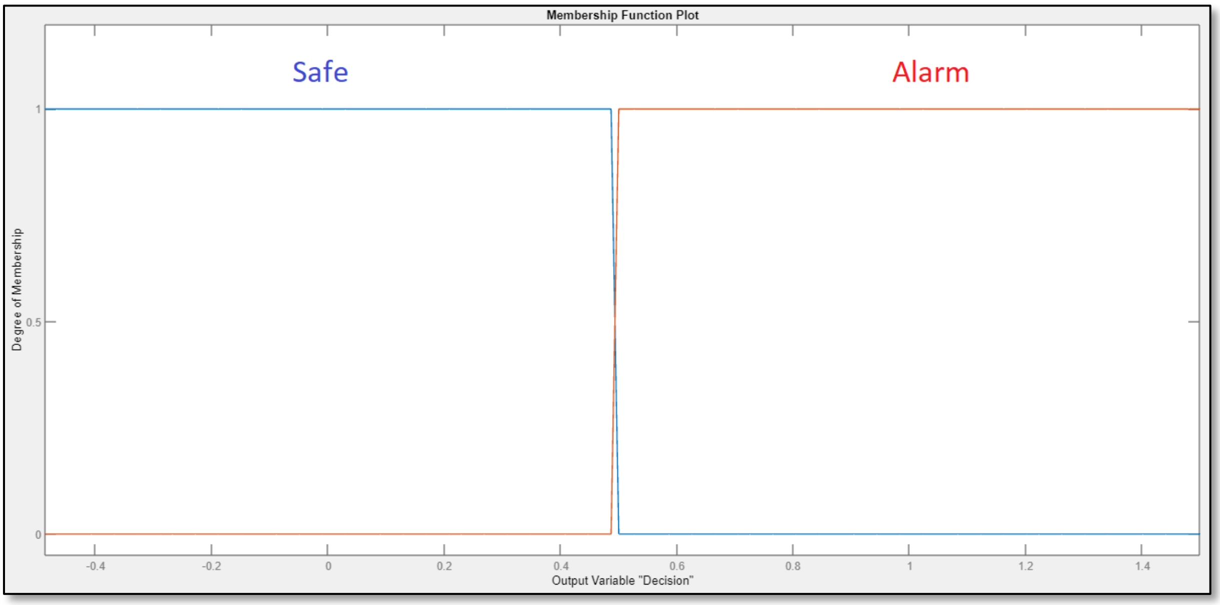


Figure IV.13: *Fuzzy Logic Fire Detection Output Membership Functions Plot*

IV.3. FIS Integration with TIA Portal:

IV.3.1. FIS SCL Code Generation:

For the SCL code generation of the previously developed fuzzy controller, MATLAB PLC Coder is used by executing the following steps:

1. Open Simulink then import a fuzzy controller block with the specified ".fis" file containing the controller's parameters.

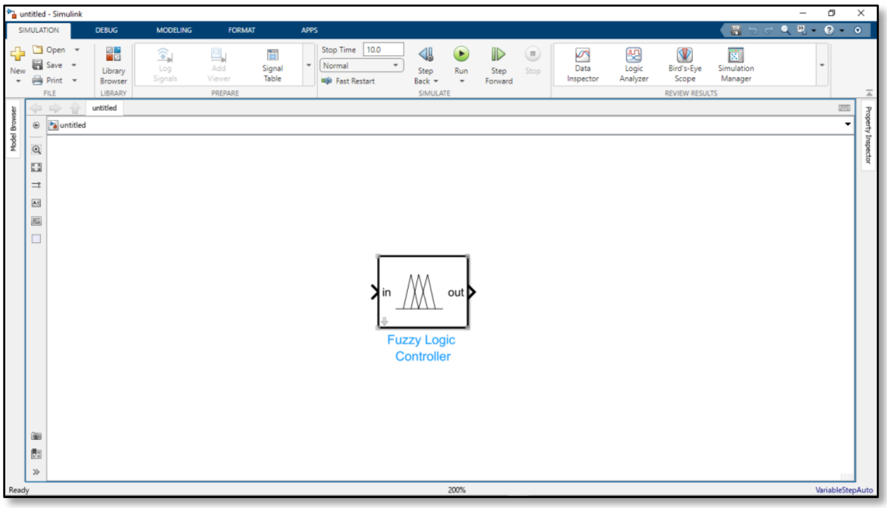


Figure IV.14: *Simulink Fuzzy Block Diagram*

2. Create a subsystem from the fuzzy controller block.

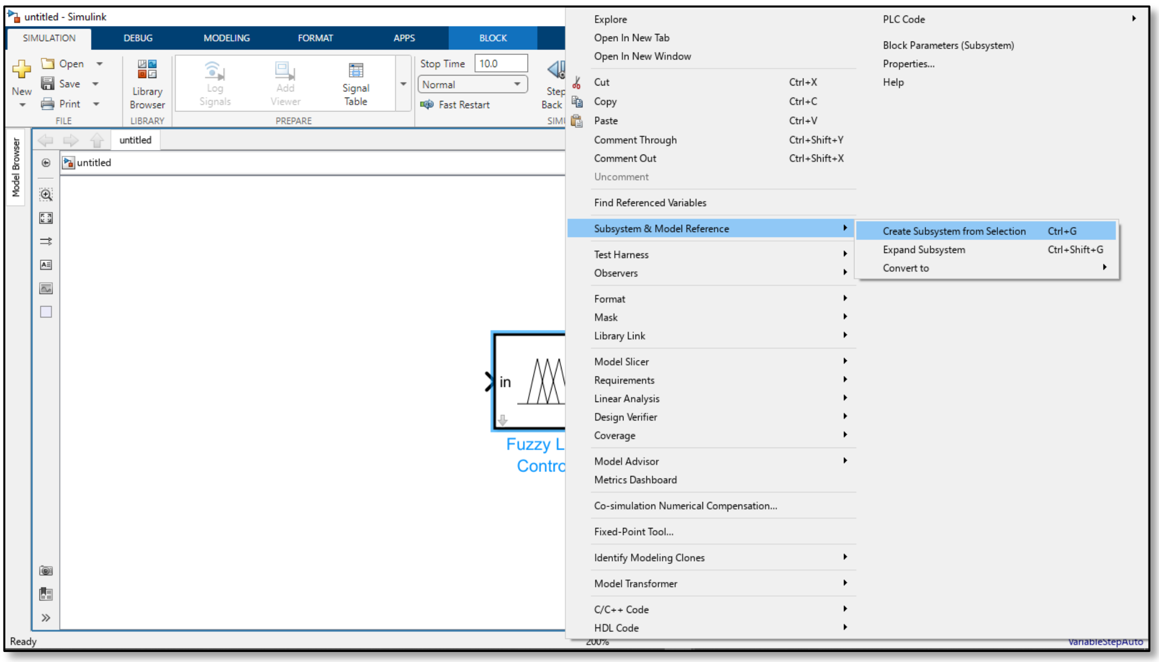


Figure IV.15: *Simulink Fuzzy Block Subsystem Creation*

3. Enable the "Treat as atomic unit" option in the subsystem's block parameters.

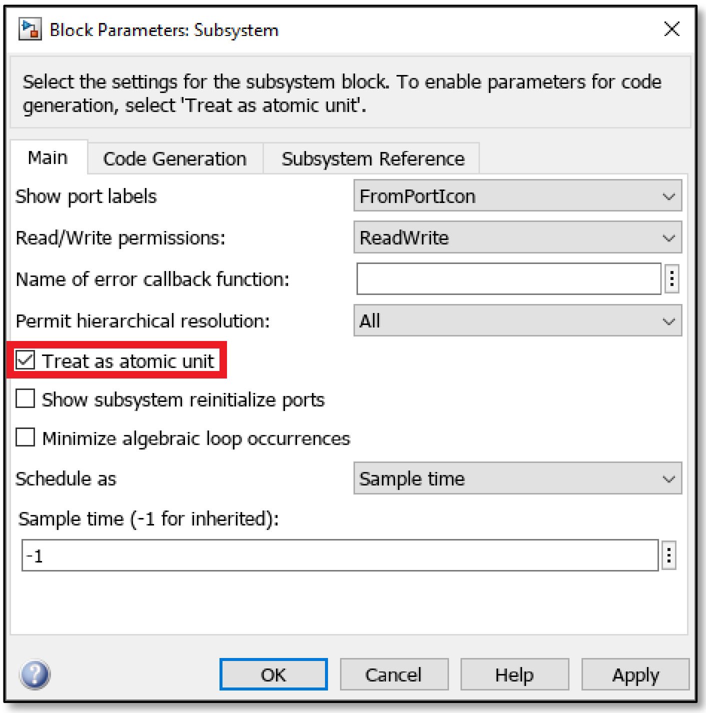


Figure IV.16: *Simulink Fuzzy Block Subsystem Parameters*

4. Choose "Siemens TIA Portal" as the Target IDE in the PLC Coder options.

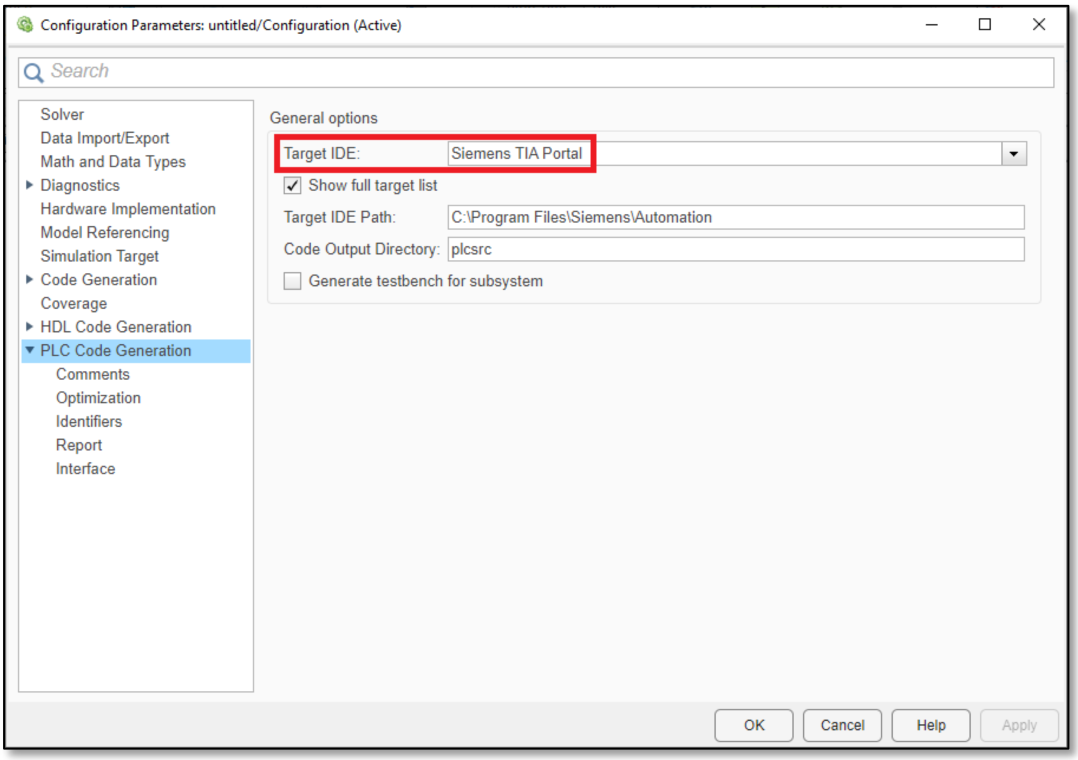


Figure IV.17: *MATLAB PLC Coder Options*

5. Click on “Generate Code for Subsystem” in the PLC Code submenu.

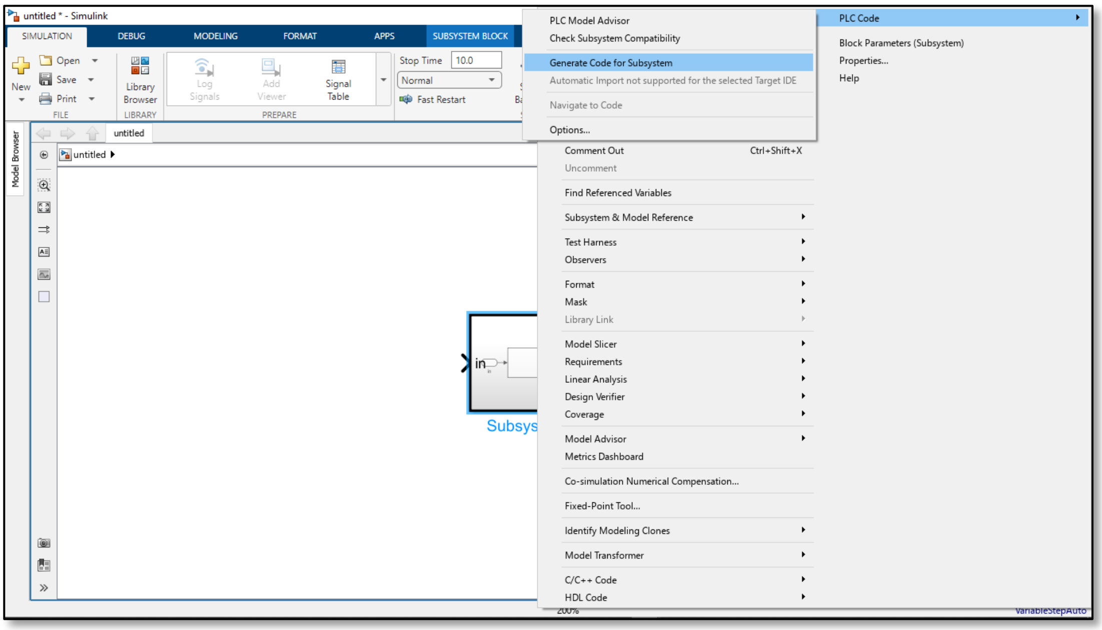


Figure IV.18: *Simulink Fuzzy Block PLC Code Generation*

The output is a Structured Control Language (SCL) file that is then imported into TIA Portal. Essentially, two program blocks are created: a function defining a trapezoidal membership function and a function block for the fuzzy inference system. The main principle involves converting the fuzzy inference system into a lookup table. This lookup table is then utilized to determine the final fire classification decision (fire or no fire) depending on the four sensors input data. The blocks’ code is available in Appendix C.

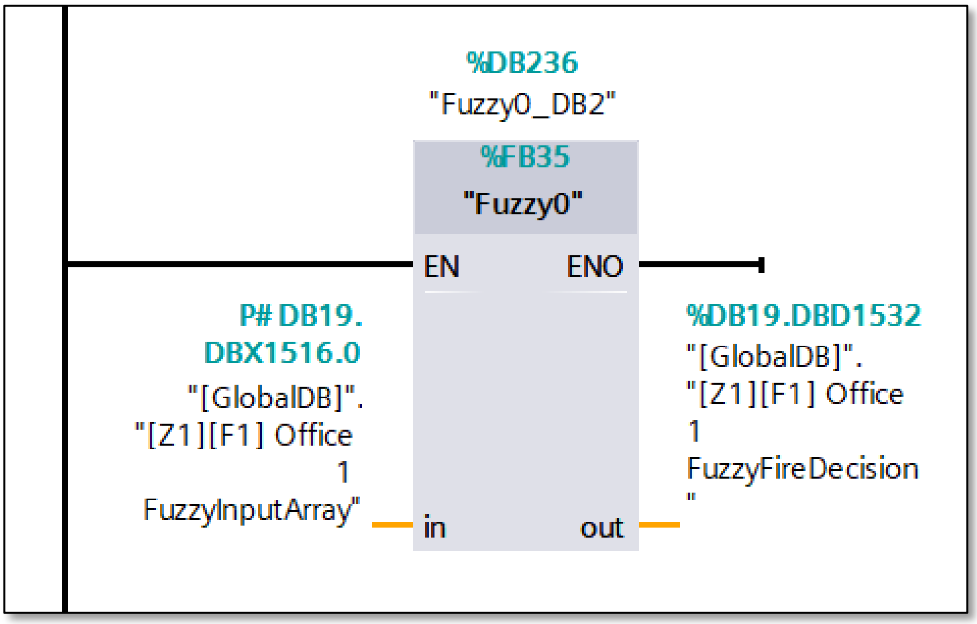


Figure IV.19: *Fuzzy Controller Function Block*

IV.3.2. FIS Inputs Data Preprocessing:

The fire sensors data has to be processed before inputted within the fuzzy function block. Notably, the data has to be normalized then scaled. The function block shown below accepts the digitized analog values from the sensors and converts them into the corresponding physical quantities such as smoke obscuration rate.

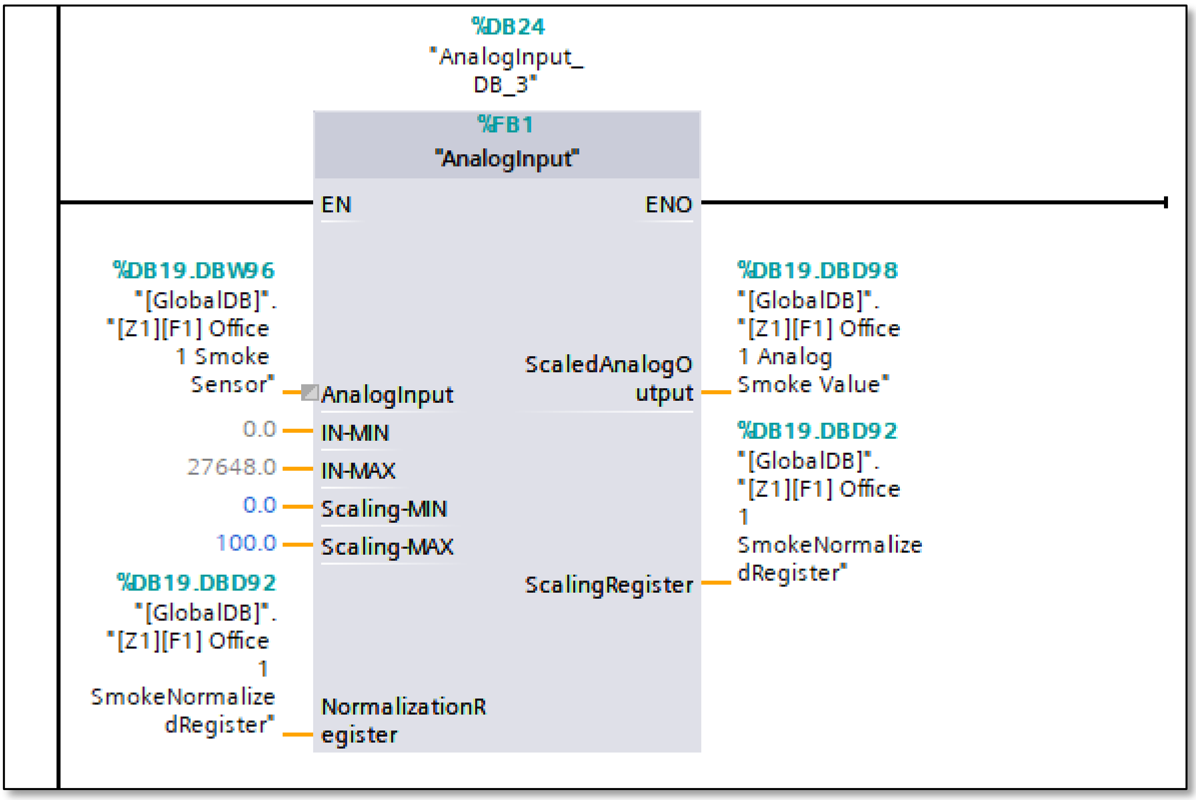


Figure IV.20: *Smoke Analog Input Function Block*

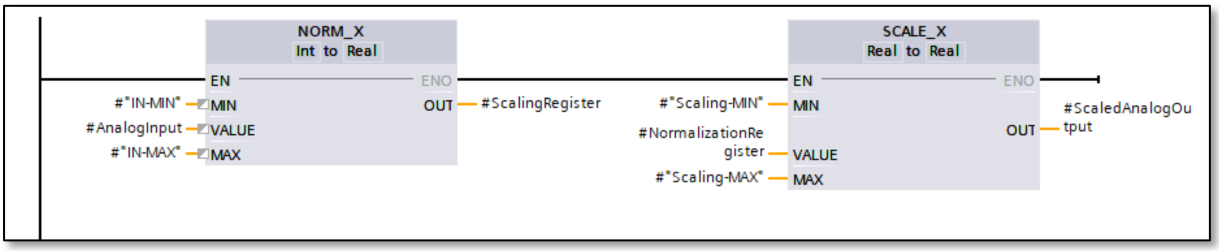


Figure IV.21: *Analog Input Function Block Operations*

IV.3.3. Fire Alarm Decision:

Fuzzy fire detectors are installed throughout the building. This includes placement in every room of every floor, as well as in the elevator and staircase. Four additional detectors are installed within the pumping room of each of the three designated fire zones. Each floor's architectural layout is provided in the figure IV.24 below. [30]

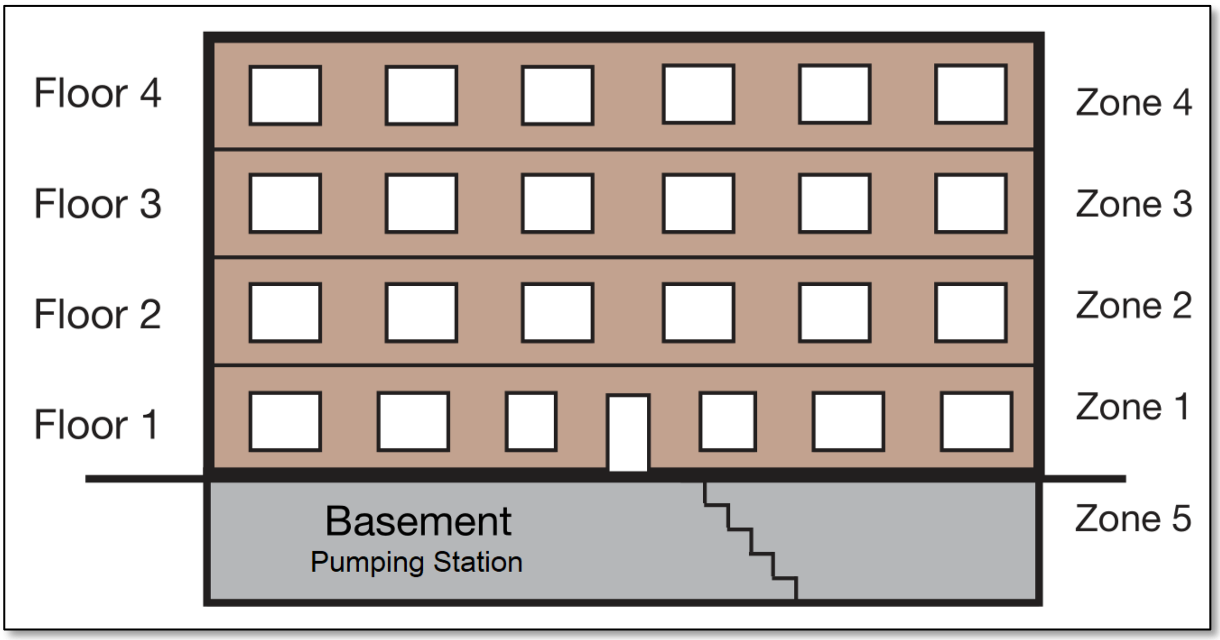


Figure IV.22: *Administrative Fire Zone Building Floors*

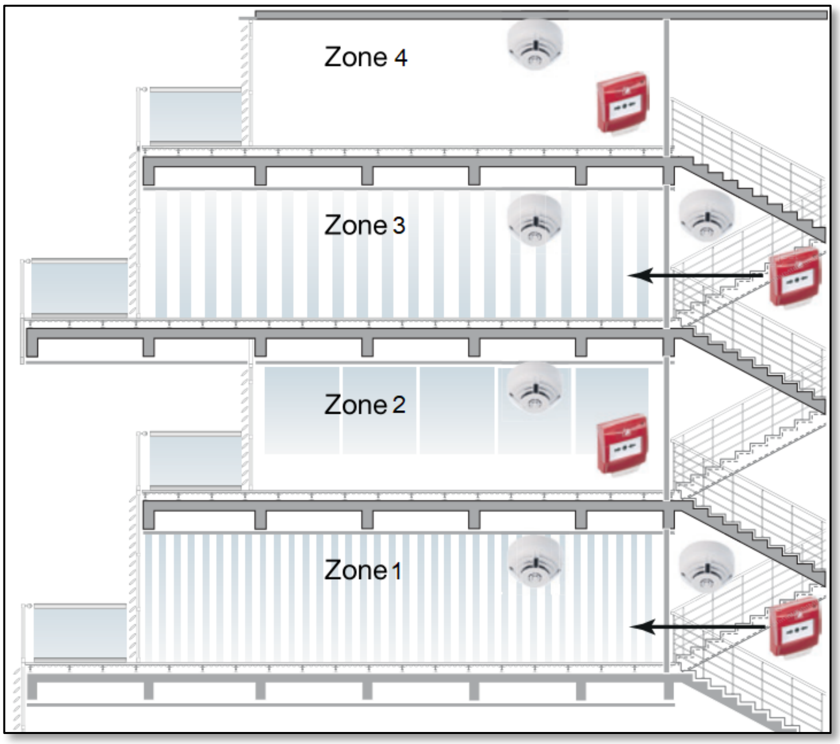


Figure IV.23: *Administrative Fire Zone Building Alarm Zones*

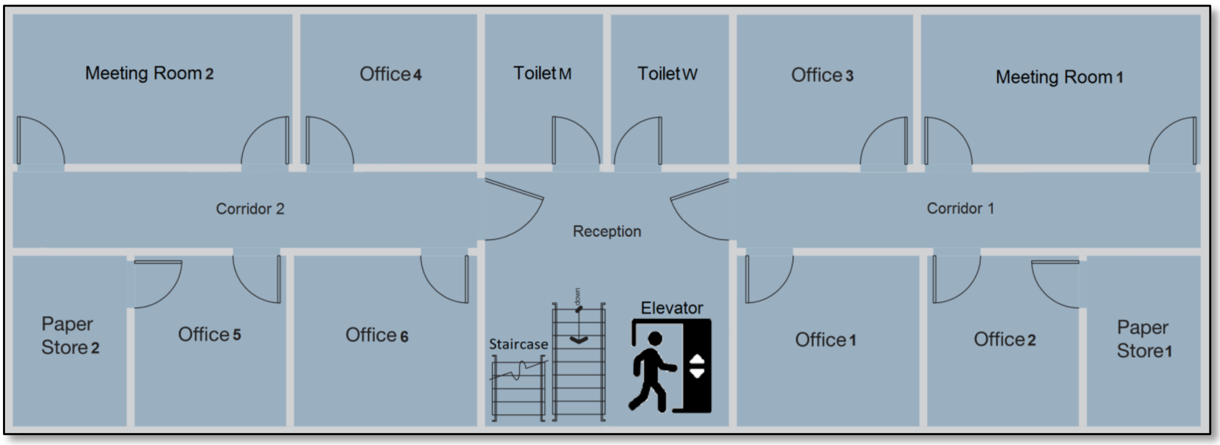


Figure IV.24: *Administrative Fire Zone Building Floor Layout*

To ensure an accurate and rapid response to potential fire hazards while minimizing false alarms, the fire alarm system is designed to trigger under any of the following conditions:

- **Manual Fire Alarm Activation:** Readily accessible manual call points are strategically located throughout the building. In each floor, six call points are easily reachable, with additional ones positioned in elevators and stairwells. Activating any of these call points will immediately trigger the fire alarm.
- **Sustained Fire Detector Activation:** If a detector is triggered and remains activated for a continuous period of 3 minutes, the fire alarm will be triggered. This time delay helps to minimize false alarms caused by temporary fluctuations or non-fire events.
- **Adjacent Room Fire Detection:** For enhanced fire awareness, the system monitors fire detectors in adjacent rooms. If a fire detector in a neighboring space is activated, the fire alarm is triggered bypassing the 3 minute delay.
- **Remote Alarm Activation via Camera System:** The fire alarm system is integrated with the building's camera surveillance system. If authorized personnel monitoring the security cameras observe a fire event, they can remotely activate the fire alarm through a designated "activate alarm" button on the camera screen. This allows for a quick response if a fire is visually identified before a detector is triggered. This also promotes early evacuation even if the fire hasn't yet directly impacted the immediate area.

IV.4. FIS Performance Assessment:

IV.4.1. FDS Simulations:

IV.4.1.1 Input File:

The FDS input is a text file that specifies the fire scenario parameters and properties. For the sake of explanation, let us consider a sample case code showcased in the figure IV.25 below.

```
&HEAD CHID='Office_Open_Corner_Small_TV_Smoldering',
      TITLE='Office_Open_Corner_Small_TV_Smoldering' /

&MESH XB= 0, 6, 0, 4, 0, 3, IJK= 60, 40, 30 /

&TIME T_END=720. /
&DUMP NFRAMES=720 /

&VENT XB= 1, 2, 4, 4, 0, 2, SURF_ID='OPEN' / door
&VENT XB= 3, 5, 0, 0, 1, 2.5, SURF_ID='OPEN' / window

&SPEC ID= 'POLYETHYLENE', FORMULA = 'C2H4', ENTHALPY_OF_FORMATION=-29E3 /
&REAC FUEL = 'POLYETHYLENE', SOOT_YIELD = 0.121, CO_YIELD = 0.01, HEAT_OF_COMBUSTION = 46E3  /
&OBST XB= 0, 0.25, 0, 0.25, 0, 0.05, COLOR='RED', SURF_ID='fire' /
&SURF ID='fire', HRRPUA=290, TAU_Q = 670. /

&DEVC ID='Temp', XYZ=3, 2, 2.8, QUANTITY='THERMOCOUPLE' /

&DEVC ID='Smoke',PROP_ID='Smoke Detector', XYZ=3, 2, 2.8, QUANTITY='CHAMBER OBSCURATION' /
&PROP ID='Smoke Detector', QUANTITY='CHAMBER OBSCURATION', LENGTH=1.8, ACTIVATION_OBSCURATION=5.63/

&DEVC ID='Radiance', QUANTITY='RADIANCE', XYZ=3, 2, 2.8, ORIENTATION=0,0,-1 /

&DEVC ID='CO', XYZ=3, 2, 2.8, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE',
      ID='CO' CONVERSION_FACTOR=1E6 UNITS='ppm'/

&TAIL /
```

Figure IV.25: *FDS Sample Input File*

- **"&HEAD" and "&TAIL":** they mark the start and end of the input file respectively.
- **"&MESH":** defines the simulation environment i.e. the dimensions of the room.
- **"&TIME":** specifies the duration of the simulation whereas the "&DUMP" operator specifies the data sampling rate; in this case, each second a sensor measurement is taken.
- **"&VENT":** defines the coordinates of an opening in the room; in this case a door and a window are defined.
- **"&SPEC" and "&REAC":** specify the combustible characteristics and the reaction properties respectively. "ENTHALPY_OF_FORMATION" is the heat of formation of the gas in (kJ/mol). Whereas, the "SOOT_YIELD" and "CO_YIELD" parameters specify the percentage of smoke and carbon monoxide released during the combustion

respectively. The "HEAT_OF_COMBUSTION" is the energy released per unit mass of fuel that mixes with oxygen and combusts.

- **"&OBST":** defines the coordinates and volume of the fire.
- **"&SURF":** specifies the Heat Release Rate Per Unit Area (HRRPUA) of the fire reaction which is essentially a measurement unit for the fire's intensity and energy emission. Additionally, the time constant of the fire reaction "TAU_Q" can be specified.
- **"&DEVC":** defines the four types of fire detectors with their measured "QUANTITY", coordinates via "XYZ" and their specific properties. [31]

To conduct a rigorous evaluation of the system, a diverse range of fire scenarios must be simulated. The tables below summarize the input parameters for each fire case. Each set of fire cases is conducted in two distinct fire locations: one situated at the center of the room and another in one of its corners. Additionally, two air flow conditions are considered: an open room configuration and a closed room configuration. The complete list of 128 fire cases is detailed in Appendix D.

Parameter Variants	Dimensions
Office	6x4x3 meters
Corridor	9x3x3 meters

Table IV.2: *FDS Input Room Type Parameter*

Depending of the type of the combustible, the combustion duration varies.

Parameter Variants	Duration
Very Short	240 seconds
Short	300 seconds
Medium	390 seconds
Long	720 seconds

Table IV.3: *FDS Input Combustion Duration Parameter [32]*

Parameter Variants	Chemical Formula	Combustion Properties	Smoke Soot Yield Coeff.	HRRPUA
Chair	$C_6H_{10}O_5$ (Cellulose)	Enthalpy of formation: -393.15 KJ/mol	Flaming: 0.0075 Smoldering: 0.08	2100 kW
Curtain	$C_6H_{10}O_5$ (Cellulose)	Enthalpy of formation: -393.15 KJ/mol	Flaming:0.0075 Smoldering: 0.08	240 kW
Television	C_2H_4 (Polyethylene)	Enthalpy of formation: -29000 KJ/mol Heat of Combustion: 46000 KJ/Kg	Flaming: 0.08 Smoldering:0.121	290 kW
Wastepaper	$C_6H_{10}O_5$ (Cellulose)	Enthalpy of formation: -393.15 KJ/mol	Flaming: 0.0075 Smoldering: 0.08	15 kW

Table IV.4: *FDS Input Fire Fuel Parameter* [32][33][34]

Parameter Variants	Volume
Small	12.5 dm^3
Large	3.125 dm^3

Table IV.5: *FDS Input Fire Combustible Volume Parameter*

IV.4.1.2 Output Files:

FDS generates two relevant output files: an SMV visual rendering of the simulation and a CSV file containing measurement data from the fire detectors. The CSV file comprises four columns of sensor data, each corresponding to one of the four types of fire sensors employed.

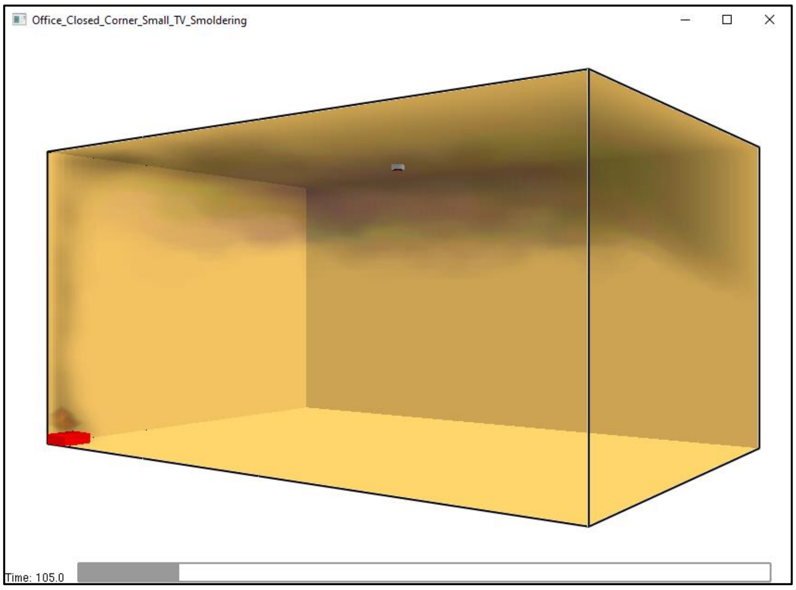


Figure IV.26: *FDS SMV Sample Output*

s	C	%/m	kW/m2/sr	ppm
Time	Temp	Smoke	Radiance	CO
164,02	27,15	34,34	0,13	3,85
165,01	27,14	34,41	0,13	3,82
166,02	27,15	34,46	0,13	3,91
167,02	27,16	34,53	0,13	4,01
168,02	27,22	34,6	0,13	4,12
169,01	27,23	34,75	0,13	3,84
170,01	27,24	34,76	0,13	4,1
171,02	27,31	34,83	0,13	4,23
172,01	27,35	34,98	0,13	4,06
173,01	27,38	35,07	0,14	4,21
174	27,46	35,21	0,14	4,38
175,01	27,55	35,45	0,14	4,5
176,02	27,66	35,61	0,14	4,66
177	27,75	35,79	0,14	4,61
178,02	27,85	35,87	0,14	4,76
179,02	27,93	36,05	0,14	4,59
180,01	28	36,14	0,14	4,74
181,01	28,07	36,28	0,14	4,67
182,02	28,12	36,46	0,14	4,74
183,01	28,22	36,61	0,14	4,92
184,01	28,28	36,79	0,14	4,75
185,02	28,34	36,84	0,14	4,94
186,01	28,42	36,96	0,14	4,89
187,02	28,46	37,11	0,14	4,73
188,01	28,48	37,23	0,14	4,78
189,01	28,52	37,34	0,14	4,95
190,02	28,57	37,53	0,14	4,85
191,02	28,57	37,8	0,14	4,65
192,02	28,63	38	0,14	5,45

Table IV.6: *FDS Sample CSV Output File*

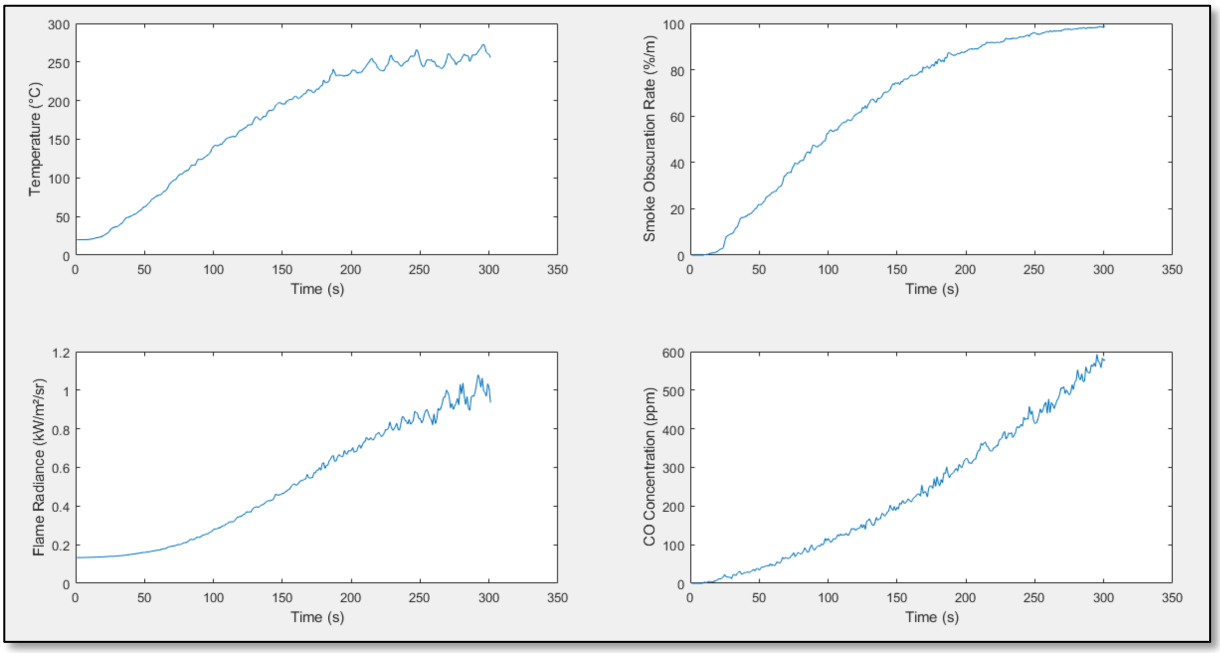


Figure IV.27: *FDS Sample Fire Sensors Data Plots*

IV.4.2. Fire Detection Algorithm System Validation:

The simulated fire sensors data is utilized to evaluate the performance of the FIS fire detection algorithm. The testing process is conducted as follows:

1. The CSV files containing the sensor data are imported into MATLAB, and then vertically concatenated to obtain a single matrix named "datain".
2. The reference output i.e. the predicted FIS output is assigned to each “datain” matrix. This labeling follows the order in which the data points exceed industry-standard fire detector thresholds. These thresholds are as follows:
   - Temperature threshold: 57 °C [35]
   - Smoke obscuration rate threshold: 5.63 %/m [36]
   - Carbon monoxide threshold: 100 ppm [29]
   - Flame radiance has no threshold since in most commercially available flame detectors, the threshold is not disclosed.
3. Utilizing the “System Validation” feature in MATLAB Fuzzy Logic Designer Toolbox, the Root Mean Square Error (RMSE) of the FIS is calculated. This metric helps us assess the accuracy of the FIS predictions compared to the reference outputs.

IV.4.3. Results & Discussion

By following the previously explained performance evaluation procedure, the resulting assessment is showcased in the figure IV.28 below.

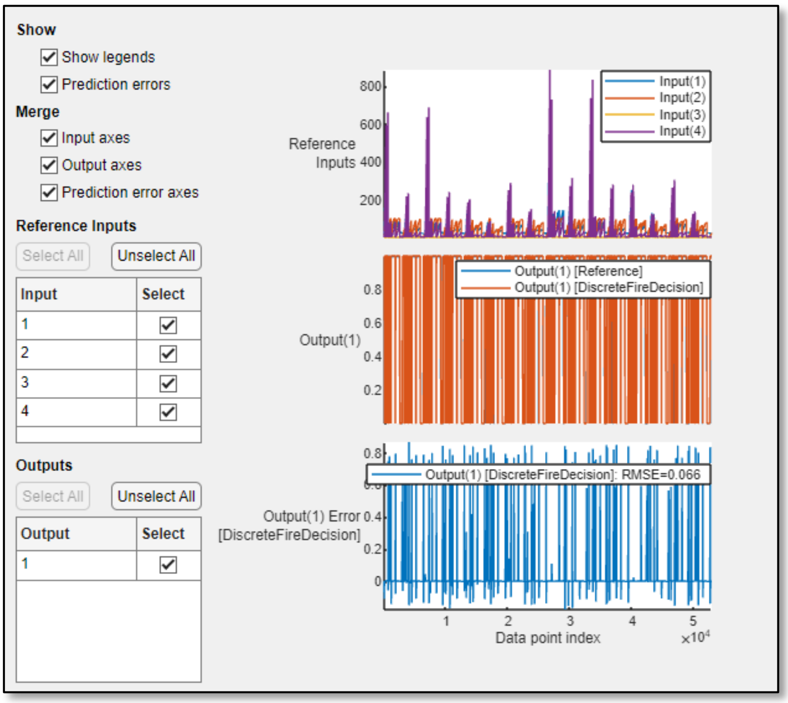


Figure IV.28: *Fuzzy Logic Fire Detection Algorithm Testing Results*

As indicated in the prediction error plot (bottom plot) of the figure IV.28 above, the resulting RMSE = 0.066. A better performance assessment metric is the Scatter Index (SI) which takes into account the range of possible FIS outputs and is calculated as follows:

$$SI = \frac{RMSE}{y} \times 100 = 6.6\% \quad \text{... (IV.2)}$$

Where "y" is the range of the FIS output. In this case, y=1.

According to these results, this FIS fire detection algorithm ranks amongst the "very good" detection algorithms.

The table IV.7 below showcases the performance parameters of the proposed approach.

Method	Detection Rate (%)	False Alarm Rate (%)	Accuracy (%)
Proposed Method	**99.74**	**2.72**	**99.27**

Table IV.7: *Fire Detection Algorithm Performance Results*

The parameters Detection Rate (DR), False Alarm Rate (FAR), and Accuracy Rate (AR) were evaluated according to the following expressions:

$$DR = \frac{TP}{TP+FN} \quad \text{... (IV.2)}$$

Where:

- TP stands for True Positives (the number of correctly detected fire instances)
- FN stands for False Negatives (the number of missed fire instances)

$$FAR = \frac{FP}{FP+TN} \quad \text{... (IV.3)}$$

Where:

- FP stands for False Positives (the number of non-fire instances incorrectly identified as fires)
- TN stands for False Negatives (the number of correctly identified non-fire instances)

Finally:

$$AR = \frac{TP+TN}{TP+TN+FP+FN} \quad \text{... (IV.4)}$$

These formulas were evaluated using the MATLAB code showcased in the figure IV.29 below.

```
fismat = readfis('FireDecision.fis');
anfis_output = evalfis(datain , fismat);
test_label = dataout;
for i=1 : length (anfis_output)
anfis_output(i)= round(anfis_output(i));
end
tp = sum((anfis_output == 1) & (test_label == 1));
fp = sum((anfis_output == 1) & (test_label == 0));
fn = sum((anfis_output == 0) & (test_label == 1));
tn = sum((anfis_output == 0) & (test_label == 0));
DetectionRate = tp / (tp + fn) *100
FalseAlarmRate = fp / (fp + tn) *100
Accuracy = (tp + tn) / (tp + tn + fp + fn) * 100
```

Figure IV.29: *FIS System Evaluation Matlab Code*

Where:

- The “evalfis” command computes the FIS output for the simulated sensor data stored in “datain”
- “dataout” is the predicted FIS classification output for every fire case.

IV.5. Conclusion:

In conclusion, this chapter explained the fire detection algorithm. The FIS with its chosen inputs, membership functions, and rule base was described. We explored the integration of the FIS with industrial automation tools and discussed the preprocessing techniques employed for sensor data. Finally, the chapter outlined the performance assessment procedure using FDS simulations and subsequent system validation to determine detection rate, false alarm rates, and accuracy results.

General Conclusion

The design and development of the smart PLC-based industrial fire safety system using fuzzy logic, as presented in this thesis, represents a note-worthy advancement in the field of fire detection and suppression systems. The results were highly promising which demonstrated and validated the detection algorithm's effectiveness and robust performance. Achieving a high detection rate of 99.74% with a low false alarm rate of 2.72% resulted in a remarkable accuracy of 99.27%. This performance positions the model in the "very good" tier of classification models, evidenced by the low RMSE of 0.066 and a SI of 6.6%. Additionally, by integrating automation technologies, supervision capabilities, this system offers a robust and adaptive solution for effective fire detection and suppression.

While this thesis demonstrates the feasibility and potential benefits of the proposed system, further research and development efforts may be undertaken to refine the system's performance, explore additional optimization techniques, and investigate its applicability across a wider range of industrial and commercial settings. Notably, testing the fire detection algorithm on a wider range of simulated fire scenarios would further solidify its reliability for real-world industrial applications. Additionally, expanding automation to encompass a wider range of equipment, aligning with industry standards, is crucial for real-world deployment.

Nonetheless, the smart PLC-based fire safety system using fuzzy logic serves as a testament to the power of integrating advanced automation, supervision, and intelligent algorithms, paving the way for more robust and adaptive fire safety solutions in the future.

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Appendix A

SIEMENS

Data sheet **6ES7516-3FN01-0AB0**


Figure similar

*** Spare part *** SIMATIC S7-1500F, CPU 1516F-3 PN/DP, central processing unit with work memory 1.5 MB for program and 5 MB for data, 1st interface: PROFINET IRT with 2-port switch, 2nd interface: PROFINET RT, 3rd interface: PROFIBUS, 10 ns bit performance, SIMATIC memory card required

General information	
Product type designation	CPU 1516F-3 PN/DP
HW functional status	FS03
Firmware version	V2.9
Product function	
• I&M data	Yes; I&M0 to I&M3
• Isochronous mode	Yes; Distributed and central; with minimum OB 6x cycle of 375 µs (distributed) and 1 ms (central)
Engineering with	
• STEP 7 TIA Portal configurable/integrated from version	V17 (FW V2.9) / V13 SP1 Update 4 (FW V1.8) or higher
Configuration control	
via dataset	Yes
Display	
Screen diagonal [cm]	6.1 cm
Control elements	
Number of keys	6
Mode selector switch	1
Supply voltage	
Rated value (DC)	24 V
permissible range, lower limit (DC)	19.2 V
permissible range, upper limit (DC)	28.8 V
Reverse polarity protection	Yes
Mains buffering	
• Mains/voltage failure stored energy time	5 ms
Input current	
Current consumption (rated value)	0.85 A
Inrush current, max.	2.4 A; Rated value
I^2t	0.02 $A^2 \cdot s$
Power	
Infeed power to the backplane bus	12 W
Power consumption from the backplane bus (balanced)	6.7 W
Power loss	
Power loss, typ.	7 W
Memory	
Number of slots for SIMATIC memory card	1
SIMATIC memory card required	Yes
Work memory	
• integrated (for program)	1.5 Mbyte
• integrated (for data)	5 Mbyte

Appendix B

	Rule	Weight	Name
1	If Temp is Cold and Smoke is Clear and Radiance is NoFlames and CO is Safe then Decision is Safe	1	rule1
2	If Temp is Cold and Smoke is Clear and Radiance is NoFlames and CO is Low_Concentration then Decision is Safe	1	rule2
3	If Temp is Cold and Smoke is Clear and Radiance is NoFlames and CO is High_Concentration then Decision is Safe	1	rule3
4	If Temp is Cold and Smoke is Clear and Radiance is Flames and CO is Safe then Decision is Safe	1	rule4
5	If Temp is Cold and Smoke is Clear and Radiance is Flames and CO is Low_Concentration then Decision is Safe	1	rule5
6	If Temp is Cold and Smoke is Clear and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule6
7	If Temp is Cold and Smoke is Low_Density and Radiance is NoFlames and CO is Safe then Decision is Safe	1	rule7
8	If Temp is Cold and Smoke is Low_Density and Radiance is NoFlames and CO is Low_Concentration then Decision is Safe	1	rule8
9	If Temp is Cold and Smoke is Low_Density and Radiance is NoFlames and CO is High_Concentration then Decision is Safe	1	rule9
10	If Temp is Cold and Smoke is Low_Density and Radiance is Flames and CO is Safe then Decision is Safe	1	rule10
11	If Temp is Cold and Smoke is Low_Density and Radiance is Flames and CO is Low_Concentration then Decision is Safe	1	rule11
12	If Temp is Cold and Smoke is Low_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule12
13	If Temp is Cold and Smoke is High_Density and Radiance is NoFlames and CO is Safe then Decision is Alarm	1	rule13
14	If Temp is Cold and Smoke is High_Density and Radiance is NoFlames and CO is Low_Concentration then Decision is Alarm	1	rule14
15	If Temp is Cold and Smoke is High_Density and Radiance is NoFlames and CO is High_Concentration then Decision is Alarm	1	rule15
16	If Temp is Cold and Smoke is High_Density and Radiance is Flames and CO is Safe then Decision is Alarm	1	rule16
17	If Temp is Cold and Smoke is High_Density and Radiance is Flames and CO is Low_Concentration then Decision is Alarm	1	rule17
18	If Temp is Cold and Smoke is High_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule18
19	If Temp is Warm and Smoke is Clear and Radiance is NoFlames and CO is Safe then Decision is Safe	1	rule19
20	If Temp is Warm and Smoke is Clear and Radiance is NoFlames and CO is Low_Concentration then Decision is Safe	1	rule20
21	If Temp is Warm and Smoke is Clear and Radiance is NoFlames and CO is High_Concentration then Decision is Safe	1	rule21
22	If Temp is Warm and Smoke is Clear and Radiance is Flames and CO is Safe then Decision is Safe	1	rule22
23	If Temp is Warm and Smoke is Clear and Radiance is Flames and CO is Low_Concentration then Decision is Safe	1	rule23
24	If Temp is Warm and Smoke is Clear and Radiance is Flames and CO is High_Concentration then Decision is Safe	1	rule24
25	If Temp is Warm and Smoke is Low_Density and Radiance is NoFlames and CO is Safe then Decision is Safe	1	rule25
26	If Temp is Warm and Smoke is Low_Density and Radiance is NoFlames and CO is Low_Concentration then Decision is Safe	1	rule26
27	If Temp is Warm and Smoke is Low_Density and Radiance is NoFlames and CO is High_Concentration then Decision is Safe	1	rule27
28	If Temp is Warm and Smoke is Low_Density and Radiance is Flames and CO is Safe then Decision is Safe	1	rule28
29	If Temp is Warm and Smoke is Low_Density and Radiance is Flames and CO is Low_Concentration then Decision is Safe	1	rule29
30	If Temp is Warm and Smoke is Low_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule30
31	If Temp is Warm and Smoke is High_Density and Radiance is NoFlames and CO is Safe then Decision is Alarm	1	rule31
32	If Temp is Warm and Smoke is High_Density and Radiance is NoFlames and CO is Low_Concentration then Decision is Alarm	1	rule32
33	If Temp is Warm and Smoke is High_Density and Radiance is NoFlames and CO is High_Concentration then Decision is Alarm	1	rule33
34	If Temp is Warm and Smoke is High_Density and Radiance is Flames and CO is Safe then Decision is Alarm	1	rule34
35	If Temp is Warm and Smoke is High_Density and Radiance is Flames and CO is Low_Concentration then Decision is Alarm	1	rule35
36	If Temp is Warm and Smoke is High_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule36
37	If Temp is Hot and Smoke is Clear and Radiance is NoFlames and CO is Safe then Decision is Safe	1	rule37
38	If Temp is Hot and Smoke is Clear and Radiance is NoFlames and CO is Low_Concentration then Decision is Safe	1	rule38
39	If Temp is Hot and Smoke is Clear and Radiance is NoFlames and CO is High_Concentration then Decision is Alarm	1	rule39
40	If Temp is Hot and Smoke is Clear and Radiance is Flames and CO is Safe then Decision is Alarm	1	rule40
41	If Temp is Hot and Smoke is Clear and Radiance is Flames and CO is Low_Concentration then Decision is Alarm	1	rule41
42	If Temp is Hot and Smoke is Clear and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule42
43	If Temp is Hot and Smoke is Low_Density and Radiance is NoFlames and CO is Safe then Decision is Safe	1	rule43
44	If Temp is Hot and Smoke is Low_Density and Radiance is NoFlames and CO is Low_Concentration then Decision is Safe	1	rule44
45	If Temp is Hot and Smoke is Low_Density and Radiance is NoFlames and CO is High_Concentration then Decision is Alarm	1	rule45
46	If Temp is Hot and Smoke is Low_Density and Radiance is Flames and CO is Safe then Decision is Safe	1	rule46
47	If Temp is Hot and Smoke is Low_Density and Radiance is Flames and CO is Low_Concentration then Decision is Safe	1	rule47
48	If Temp is Hot and Smoke is Low_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule48
49	If Temp is Hot and Smoke is High_Density and Radiance is NoFlames and CO is Safe then Decision is Alarm	1	rule49
50	If Temp is Hot and Smoke is High_Density and Radiance is NoFlames and CO is Low_Concentration then Decision is Alarm	1	rule50
51	If Temp is Hot and Smoke is High_Density and Radiance is NoFlames and CO is High_Concentration then Decision is Alarm	1	rule51
52	If Temp is Hot and Smoke is High_Density and Radiance is Flames and CO is Safe then Decision is Alarm	1	rule52
53	If Temp is Hot and Smoke is High_Density and Radiance is Flames and CO is Low_Concentration then Decision is Alarm	1	rule53
54	If Temp is Hot and Smoke is High_Density and Radiance is Flames and CO is High_Concentration then Decision is Alarm	1	rule54

Appendix C

Fuzzy Block SCL Code

```
(* Outputs for Atomic SubSystem: '<Root>/Fuzzy Logic  Controller' *)
(* MATLAB Function: '<S1>/Evaluate Rule Antecedents' *)
(* MATLAB Function 'Evaluate Rule Antecedents': '<S3>:1' *)
(* '<S3>:1:4' if SimulateUsing==1 && coder.internal.canUseExtrinsic ... *)
(* '<S3>:1:5'         && (isa(inputs,'double') || isa(inputs,'single')) *)
(* '<S3>:1:32' else *)
(* '<S3>:1:33' if fis.inputFuzzySetType==1 *)
(* '<S3>:1:34' [antecedentOutputs,sumAntecedentOutputs] = ... *)
(* '<S3>:1:35'             fuzzy.internal.codegen.evaluateRuleAntecedent(... *)
(* '<S3>:1:36'             inputs,fis,diagnostics); *)
#c_rtb_defuzzifiedOut := 0.0;
#inputMFCache[0] := "trapmf"(x := #in[0], params := #b_b);
#inputMFCache[1] := "trapmf"(x := #in[0], params := #b_c);
#inputMFCache[2] := "trapmf"(x := #in[0], params := #b_d);
#inputMFCache[3] := "trapmf"(x := #in[1], params := #e);
#inputMFCache[4] := "trapmf"(x := #in[1], params := #f);
#inputMFCache[5] := "trapmf"(x := #in[1], params := #g);
#inputMFCache[6] := 0.0;
IF #in[2] < 7.5 THEN
    #inputMFCache[6] := 1.0;
END_IF;
#inputMFCache[7] := 0.0;
IF #in[2] >= 7.5 THEN
    #inputMFCache[7] := 1.0;
END_IF;
#inputMFCache[8] := "trapmf"(x := #in[3], params := #h);
#inputMFCache[9] := 0.0;
IF #in[3] > 40.0 THEN
    IF #in[3] < 70.0 THEN
        #inputMFCache[9] := (#in[3] - 40.0) * 0.033333333333333333;
    END_IF;
END_IF;
IF #in[3] > 70.0 THEN
    IF #in[3] < 100.0 THEN
        #inputMFCache[9] := (100.0 - #in[3]) * 0.033333333333333333;
    END_IF;
END_IF;
IF #in[3] = 70.0 THEN
    #inputMFCache[9] := 1.0;
END_IF;
#inputMFCache[10] := "trapmf"(x := #in[3], params := #b_i);
(* End of Outputs for SubSystem: '<Root>/Fuzzy Logic  Controller' *)
(* Outputs for Atomic SubSystem: '<Root>/Fuzzy Logic  Controller' *)
(* MATLAB Function: '<S1>/Evaluate Rule Antecedents' *)
FOR #ruleID := 0 TO 53 DO
    #x_idx_1 := #inputMFCache[INT_TO_DINT(#j[#ruleID]) - 1];
    IF #x_idx_1 < 1.0 THEN
        #d_rtb_antecedentOutp := #x_idx_1;
    ELSE
        #d_rtb_antecedentOutp := 1.0;
    END_IF;
    #x_idx_1 := #inputMFCache[INT_TO_DINT(#j[#ruleID + 54]) + 2];
    IF #d_rtb_antecedentOutp > #x_idx_1 THEN
        #d_rtb_antecedentOutp := #x_idx_1;
    END_IF;
    #x_idx_1 := #inputMFCache[INT_TO_DINT(#j[#ruleID + 108]) + 5];
    IF #d_rtb_antecedentOutp > #x_idx_1 THEN
        #d_rtb_antecedentOutp := #x_idx_1;
    END_IF;
    #x_idx_1 := #inputMFCache[INT_TO_DINT(#j[#ruleID + 162]) + 7];
    IF #d_rtb_antecedentOutp > #x_idx_1 THEN
        #d_rtb_antecedentOutp := #x_idx_1;
    END_IF;
    #c_rtb_antecedentOutp[#ruleID] := #d_rtb_antecedentOutp;
    #c_rtb_defuzzifiedOut := #c_rtb_defuzzifiedOut + #d_rtb_antecedentOutp;
END_FOR;
```

Appendix C

```
(* MATLAB Function: '<S1>/Evaluate Rule Consequents' *)
(* MATLAB Function 'Evaluate Rule Consequents': '<S4>:1' *)
(* '<S4>:1:4' if SimulateUsing==1 && coder.internal.canUseExtrinsic ... *)
(* '<S4>:1:5'         && (isa(inputs,'double') || isa(inputs,'single')) *)
(* '<S4>:1:55' else *)
(* '<S4>:1:56' if fis.inputFuzzySetType==1 *)
(* '<S4>:1:57' if strcmp(char(fis.type),'mamdani') *)
(* '<S4>:1:58' aggregatedOutputs = ... *)
(* '<S4>:1:59'                 fuzzy.internal.codegen.evaluateRuleConsequentForMamdaniFIS(... *)
(* '<S4>:1:60'                 antecedentOutputs,fis,samplePoints); *)
(* End of Outputs for SubSystem: '<Root>/Fuzzy Logic  Controller' *)
(* Outputs for Atomic SubSystem: '<Root>/Fuzzy Logic  Controller' *)
(* MATLAB Function: '<S1>/Evaluate Rule Consequents' incorporates:
 *  Constant: '<S1>/Output Sample Points' *)
FOR #ruleID := 0 TO 100 DO
    #c_rtb_aggregatedOutp[#ruleID] := 0.0;
    #inputID := 0;
    #x_idx_1 := #c_OutputSamplePoints[#ruleID];
    IF #x_idx_1 < 0.5 THEN
        #inputID := 1;
    END_IF;
    #outputMFCache_tmp := DWORD_TO_DINT(SHL(IN := DINT_TO_DWORD(#ruleID), N := 1));
    #outputMFCache[#outputMFCache_tmp] := DINT_TO_INT(#inputID);
    #inputID := 0;
    IF #x_idx_1 >= 0.5 THEN
        #inputID := 1;
    END_IF;
    #outputMFCache[#outputMFCache_tmp + 1] := DINT_TO_INT(#inputID);
END_FOR;
FOR #ruleID := 0 TO 53 DO
    #x_idx_1 := #c_rtb_antecedentOutp[#ruleID];
    FOR #inputID := 0 TO 100 DO
        #d_rtb_antecedentOutp := DINT_TO_REAL(INT_TO_DINT(#outputMFCache[((#inputID * 2) + INT_TO_DINT(#c_b[#ruleID])) - 1]));
        IF #d_rtb_antecedentOutp > #x_idx_1 THEN
            #mfVal := #x_idx_1;
        ELSE
            #mfVal := #d_rtb_antecedentOutp;
        END_IF;
        #d_rtb_antecedentOutp := #c_rtb_aggregatedOutp[#inputID];
        IF #d_rtb_antecedentOutp < #mfVal THEN
            #c_rtb_aggregatedOutp[#inputID] := #mfVal;
        ELSE
            #c_rtb_aggregatedOutp[#inputID] := #d_rtb_antecedentOutp;
        END_IF;
    END_FOR;
END_FOR;
(* MATLAB Function: '<S1>/Defuzzify Outputs' incorporates:
 *  Constant: '<S1>/Output Sample Points'
 *  MATLAB Function: '<S1>/Evaluate Rule Antecedents' *)
(* MATLAB Function 'Defuzzify Outputs': '<S2>:1' *)
(* '<S2>:1:4' if SimulateUsing==1 && coder.internal.canUseExtrinsic ... *)
(* '<S2>:1:5'         && (isa(aggregatedOutputs,'double') || isa(aggregatedOutputs,'single')) *)
(* '<S2>:1:63' else *)
(* '<S2>:1:64' if fis.inputFuzzySetType==1 *)
(* '<S2>:1:65' if isequal(fis.type,uint8('mamdani')) *)
(* '<S2>:1:66' defuzzifiedOutputs = ... *)
(* '<S2>:1:67'                 fuzzy.internal.codegen.applyMamdaniDefuzzificationMethod(... *)
(* '<S2>:1:68'                 samplePoints,sumAntecedentOutputs,aggregatedOutputs, ... *)
(* '<S2>:1:69'                 fis,diagnostics); *)
IF #c_rtb_defuzzifiedOut = 0.0 THEN
    (* Outport: '<Root>/out' *)
    #out := 0.50662251655629154;
ELSE
    #c_rtb_defuzzifiedOut := 0.0;
    #mfVal := 0.0;
    FOR #ruleID := 0 TO 100 DO
        #mfVal := #mfVal + #c_rtb_aggregatedOutp[#ruleID];
    END_FOR;
    IF #mfVal = 0.0 THEN
        (* Outport: '<Root>/out' *)
        #out := 0.50662251655629154;
    ELSE
        FOR #ruleID := 0 TO 100 DO
            #c_rtb_defuzzifiedOut := (#c_OutputSamplePoints[#ruleID] * #c_rtb_aggregatedOutp[#ruleID]) + #c_rtb_defuzzifiedOut;
        END_FOR;
        (* Outport: '<Root>/out' incorporates:
         *  Constant: '<S1>/Output Sample Points' *)
        #out := (1.0 / #mfVal) * #c_rtb_defuzzifiedOut;
    END_IF;
END_IF;
(* End of MATLAB Function: '<S1>/Defuzzify Outputs' *)
(* End of Outputs for SubSystem: '<Root>/Fuzzy Logic  Controller' *)
```

Appendix C

Trapezoidal Membership Function Block SCL Code

```
#b_x := 0.0;
#b_y := 0.0;
IF #x >= #params[1] THEN
    #b_x := 1.0;
END_IF;
IF #x < #params[0] THEN
    #b_x := 0.0;
END_IF;
IF #params[0] <= #x THEN
    IF #x < #params[1] THEN
        IF #params[0] <> #params[1] THEN
            #b_x := (1.0 / (#params[1] - #params[0])) * (#x - #params[0]);
        END_IF;
    END_IF;
END_IF;
IF #x <= #params[2] THEN
    #b_y := 1.0;
END_IF;
IF #x > #params[3] THEN
    #b_y := 0.0;
END_IF;
IF #params[2] < #x THEN
    IF #x <= #params[3] THEN
        IF #params[2] <> #params[3] THEN
            #b_y := (1.0 / (#params[3] - #params[2])) * (#params[3] - #x);
        END_IF;
    END_IF;
END_IF;
#trapmf := MIN(IN1 := #b_x, IN2 := #b_y);
```

Appendix D

All FDS Simulation Cases

No.	Room	Air Flow	Location	Size	Material	Type
1.	Office	Closed	Center	Large	Chair	Flaming
2.	Office	Closed	Center	Large	Chair	Smoldering
3.	Office	Closed	Center	Large	Curtain	Flaming
4.	Office	Closed	Center	Large	Curtain	Smoldering
5.	Office	Closed	Center	Large	TV	Flaming
6.	Office	Closed	Center	Large	TV	Smoldering
7.	Office	Closed	Center	Large	Wastepaper	Flaming
8.	Office	Closed	Center	Large	Wastepaper	Smoldering
9.	Office	Closed	Center	Small	Chair	Flaming
10.	Office	Closed	Center	Small	Chair	Smoldering
11.	Office	Closed	Center	Small	Curtain	Flaming
12.	Office	Closed	Center	Small	Curtain	Smoldering
13.	Office	Closed	Center	Small	TV	Flaming
14.	Office	Closed	Center	Small	TV	Smoldering
15.	Office	Closed	Center	Small	Wastepaper	Flaming
16.	Office	Closed	Center	Small	Wastepaper	Smoldering
17.	Office	Closed	Corner	Large	Chair	Flaming
18.	Office	Closed	Corner	Large	Chair	Smoldering
19.	Office	Closed	Corner	Large	Curtain	Flaming
20.	Office	Closed	Corner	Large	Curtain	Smoldering
21.	Office	Closed	Corner	Large	TV	Flaming
22.	Office	Closed	Corner	Large	TV	Smoldering
23.	Office	Closed	Corner	Large	Wastepaper	Flaming
24.	Office	Closed	Corner	Large	Wastepaper	Smoldering
25.	Office	Closed	Corner	Small	Chair	Flaming
26.	Office	Closed	Corner	Small	Chair	Smoldering
27.	Office	Closed	Corner	Small	Curtain	Flaming
28.	Office	Closed	Corner	Small	Curtain	Smoldering
29.	Office	Closed	Corner	Small	TV	Flaming
30.	Office	Closed	Corner	Small	TV	Smoldering
31.	Office	Closed	Corner	Small	Wastepaper	Flaming
32.	Office	Closed	Corner	Small	Wastepaper	Smoldering
33.	Office	Open	Center	Large	Chair	Flaming
34.	Office	Open	Center	Large	Chair	Smoldering
35.	Office	Open	Center	Large	Curtain	Flaming
36.	Office	Open	Center	Large	Curtain	Smoldering
37.	Office	Open	Center	Large	TV	Flaming
38.	Office	Open	Center	Large	TV	Smoldering
39.	Office	Open	Center	Large	Wastepaper	Flaming
40.	Office	Open	Center	Large	Wastepaper	Smoldering
41.	Office	Open	Center	Small	Chair	Flaming
42.	Office	Open	Center	Small	Chair	Smoldering
43.	Office	Open	Center	Small	Curtain	Flaming
44.	Office	Open	Center	Small	Curtain	Smoldering
45.	Office	Open	Center	Small	TV	Flaming

46.	Office	Open	Center	Small	TV	Smoldering
47.	Office	Open	Center	Small	Wastepaper	Flaming
48.	Office	Open	Center	Small	Wastepaper	Smoldering
49.	Office	Open	Corner	Large	Chair	Flaming
50.	Office	Open	Corner	Large	Chair	Smoldering
51.	Office	Open	Corner	Large	Curtain	Flaming
52.	Office	Open	Corner	Large	Curtain	Smoldering
53.	Office	Open	Corner	Large	TV	Flaming
54.	Office	Open	Corner	Large	TV	Smoldering
55.	Office	Open	Corner	Large	Wastepaper	Flaming
56.	Office	Open	Corner	Large	Wastepaper	Smoldering
57.	Office	Open	Corner	Small	Chair	Flaming
58.	Office	Open	Corner	Small	Chair	Smoldering
59.	Office	Open	Corner	Small	Curtain	Flaming
60.	Office	Open	Corner	Small	Curtain	Smoldering
61.	Office	Open	Corner	Small	TV	Flaming
62.	Office	Open	Corner	Small	TV	Smoldering
63.	Office	Open	Corner	Small	Wastepaper	Flaming
64.	Office	Open	Corner	Small	Wastepaper	Smoldering
65.	Corridor	Closed	Center	Large	Chair	Flaming
66.	Corridor	Closed	Center	Large	Chair	Smoldering
67.	Corridor	Closed	Center	Large	Curtain	Flaming
68.	Corridor	Closed	Center	Large	Curtain	Smoldering
69.	Corridor	Closed	Center	Large	TV	Flaming
70.	Corridor	Closed	Center	Large	TV	Smoldering
71.	Corridor	Closed	Center	Large	Wastepaper	Flaming
72.	Corridor	Closed	Center	Large	Wastepaper	Smoldering
73.	Corridor	Closed	Center	Small	Chair	Flaming
74.	Corridor	Closed	Center	Small	Chair	Smoldering
75.	Corridor	Closed	Center	Small	Curtain	Flaming
76.	Corridor	Closed	Center	Small	Curtain	Smoldering
77.	Corridor	Closed	Center	Small	TV	Flaming
78.	Corridor	Closed	Center	Small	TV	Smoldering
79.	Corridor	Closed	Center	Small	Wastepaper	Flaming
80.	Corridor	Closed	Center	Small	Wastepaper	Smoldering
81.	Corridor	Closed	Corner	Large	Chair	Flaming
82.	Corridor	Closed	Corner	Large	Chair	Smoldering
83.	Corridor	Closed	Corner	Large	Curtain	Flaming
84.	Corridor	Closed	Corner	Large	Curtain	Smoldering
85.	Corridor	Closed	Corner	Large	TV	Flaming
86.	Corridor	Closed	Corner	Large	TV	Smoldering
87.	Corridor	Closed	Corner	Large	Wastepaper	Flaming
88.	Corridor	Closed	Corner	Large	Wastepaper	Smoldering
89.	Corridor	Closed	Corner	Small	Chair	Flaming
90.	Corridor	Closed	Corner	Small	Chair	Smoldering
91.	Corridor	Closed	Corner	Small	Curtain	Flaming
92.	Corridor	Closed	Corner	Small	Curtain	Smoldering
93.	Corridor	Closed	Corner	Small	TV	Flaming

94.	Corridor	Closed	Corner	Small	TV	Smoldering
95.	Corridor	Closed	Corner	Small	Wastepaper	Flaming
96.	Corridor	Closed	Corner	Small	Wastepaper	Smoldering
97.	Corridor	Open	Center	Large	Chair	Flaming
98.	Corridor	Open	Center	Large	Chair	Smoldering
99.	Corridor	Open	Center	Large	Curtain	Flaming
100.	Corridor	Open	Center	Large	Curtain	Smoldering
101.	Corridor	Open	Center	Large	TV	Flaming
102.	Corridor	Open	Center	Large	TV	Smoldering
103.	Corridor	Open	Center	Large	Wastepaper	Flaming
104.	Corridor	Open	Center	Large	Wastepaper	Smoldering
105.	Corridor	Open	Center	Small	Chair	Flaming
106.	Corridor	Open	Center	Small	Chair	Smoldering
107.	Corridor	Open	Center	Small	Curtain	Flaming
108.	Corridor	Open	Center	Small	Curtain	Smoldering
109.	Corridor	Open	Center	Small	TV	Flaming
110.	Corridor	Open	Center	Small	TV	Smoldering
111.	Corridor	Open	Center	Small	Wastepaper	Flaming
112.	Corridor	Open	Center	Small	Wastepaper	Smoldering
113.	Corridor	Open	Corner	Large	Chair	Flaming
114.	Corridor	Open	Corner	Large	Chair	Smoldering
115.	Corridor	Open	Corner	Large	Curtain	Flaming
116.	Corridor	Open	Corner	Large	Curtain	Smoldering
117.	Corridor	Open	Corner	Large	TV	Flaming
118.	Corridor	Open	Corner	Large	TV	Smoldering
119.	Corridor	Open	Corner	Large	Wastepaper	Flaming
120.	Corridor	Open	Corner	Large	Wastepaper	Smoldering
121.	Corridor	Open	Corner	Small	Chair	Flaming
122.	Corridor	Open	Corner	Small	Chair	Smoldering
123.	Corridor	Open	Corner	Small	Curtain	Flaming
124.	Corridor	Open	Corner	Small	Curtain	Smoldering
125.	Corridor	Open	Corner	Small	TV	Flaming
126.	Corridor	Open	Corner	Small	TV	Smoldering
127.	Corridor	Open	Corner	Small	Wastepaper	Flaming
128.	Corridor	Open	Corner	Small	Wastepaper	Smoldering

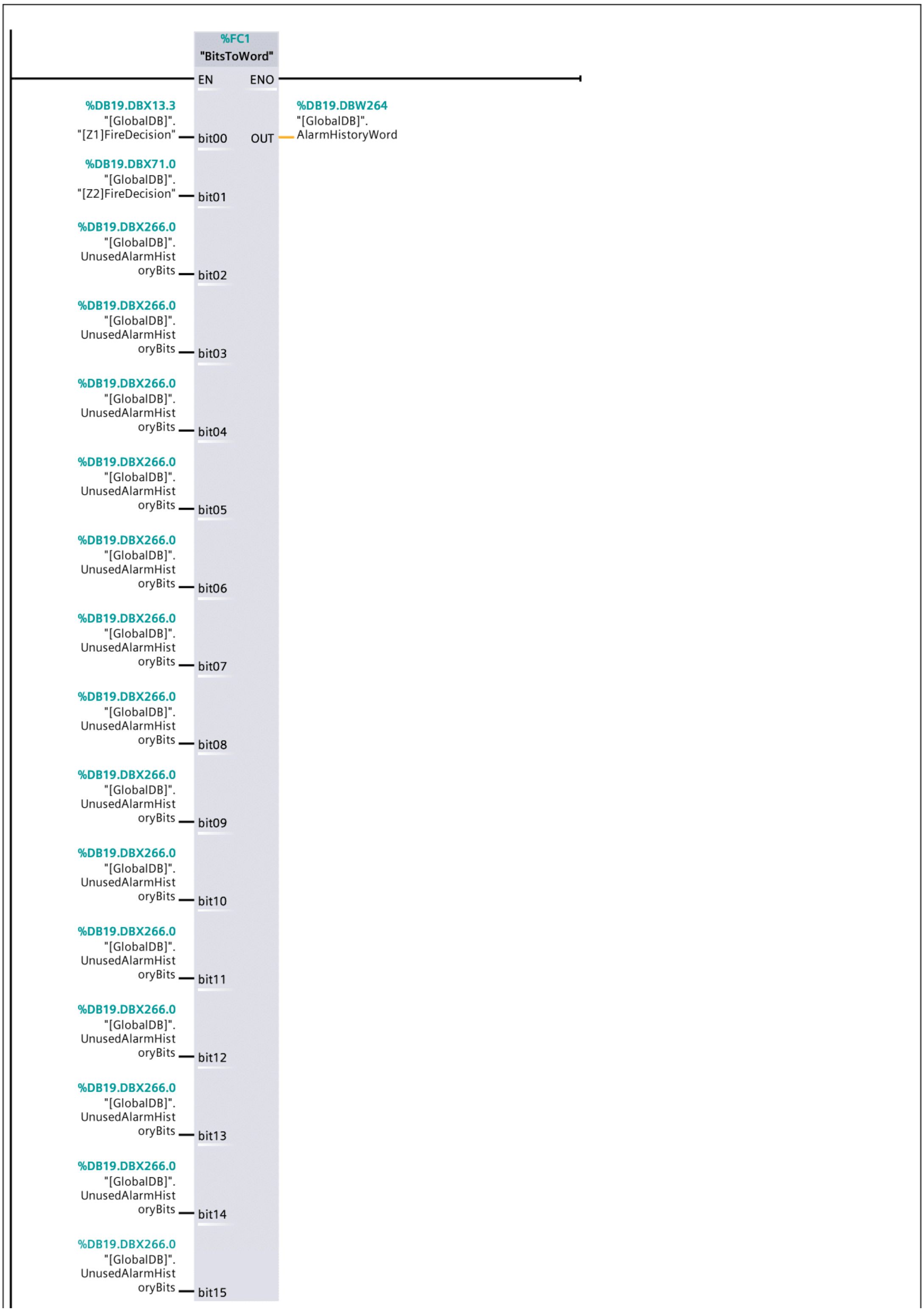
Appendix E

Ladder Program Sample Screenshots

<u>Main OB1</u>:

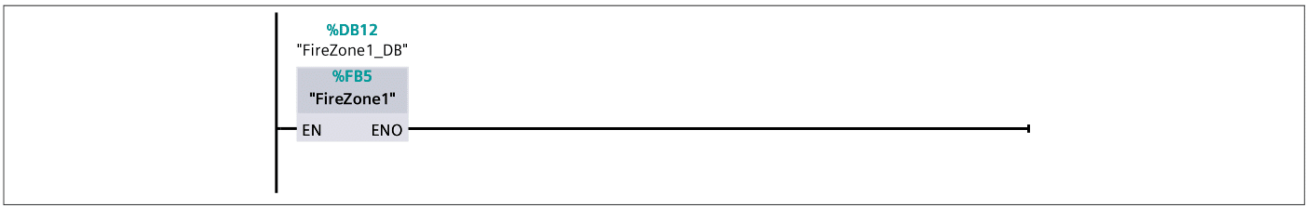
Totally Integrated Automation Portal

Network 4: (1.1 / 2.1)

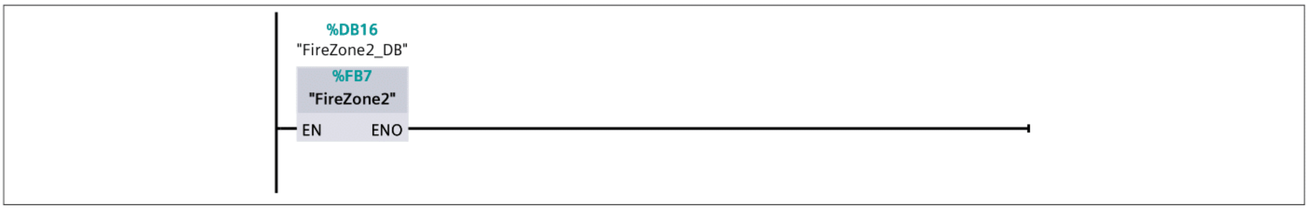


Appendix E

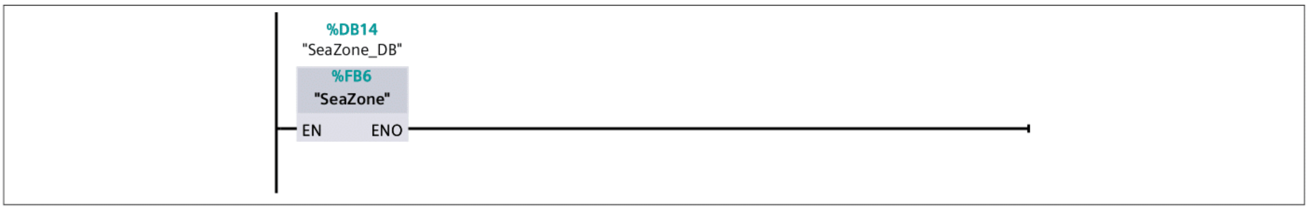
Network 1:



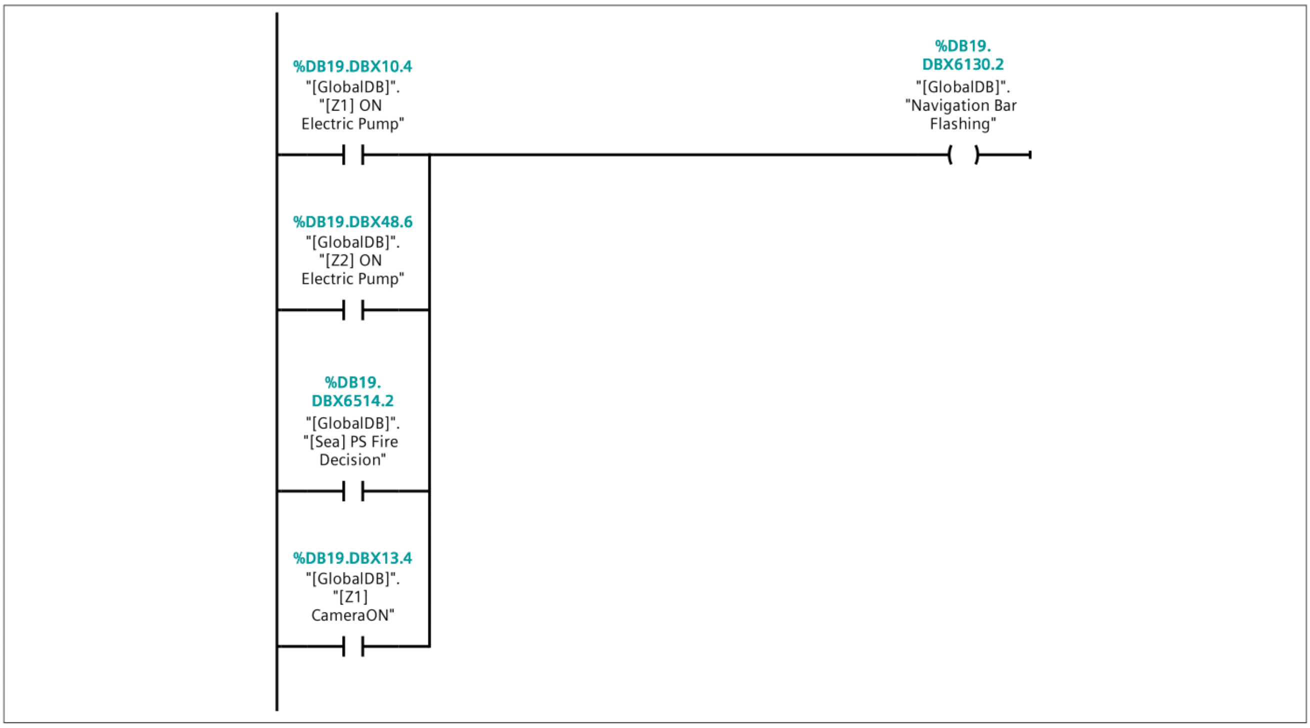
Network 2:



Network 3:



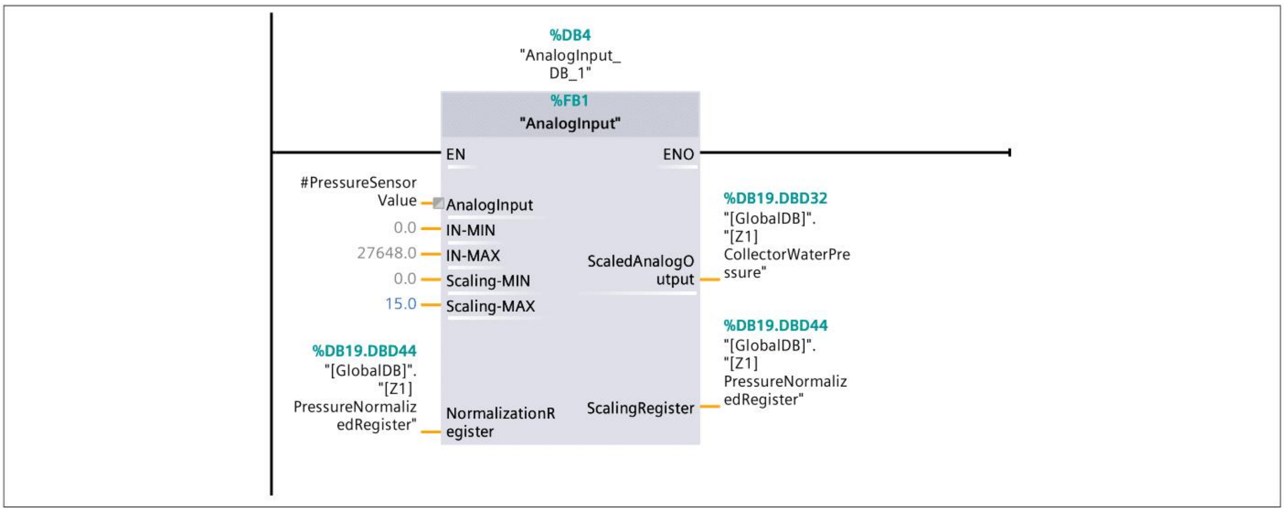
Network 5:



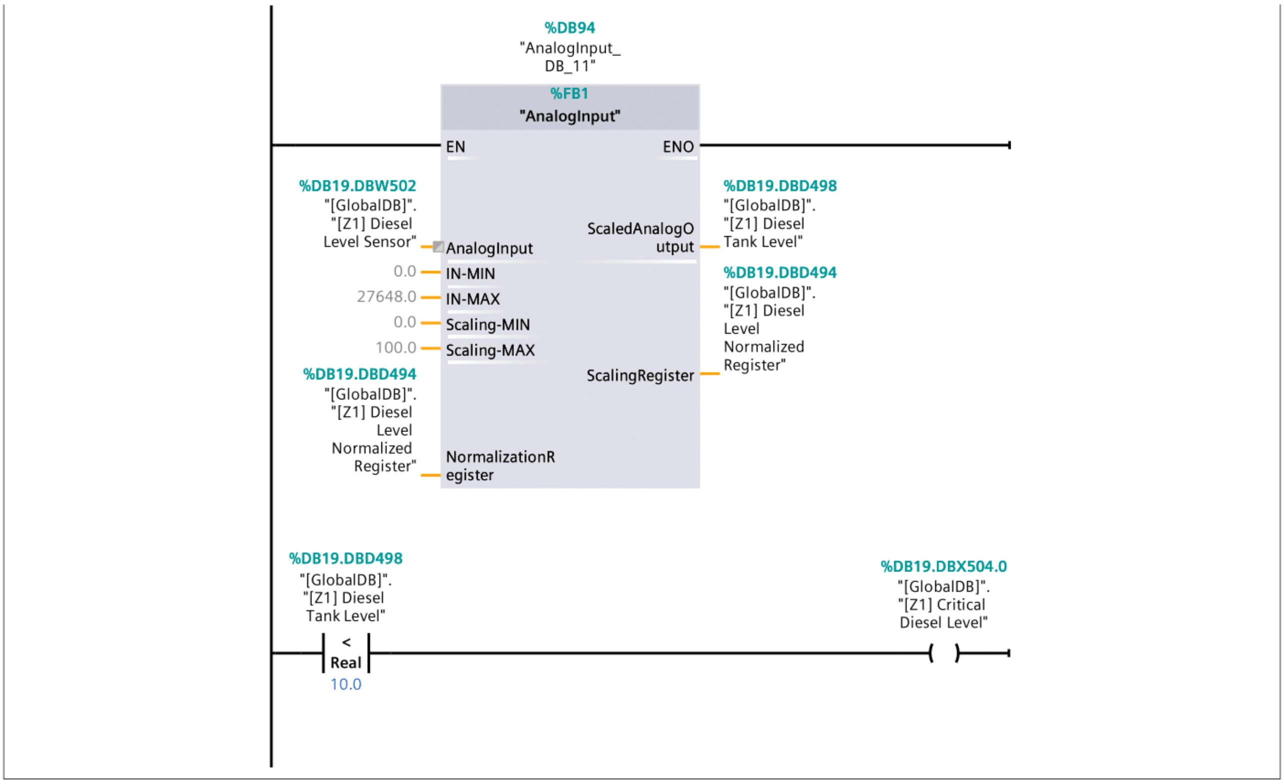
Appendix E

<u>Administrative Zone Pumping Station:</u>

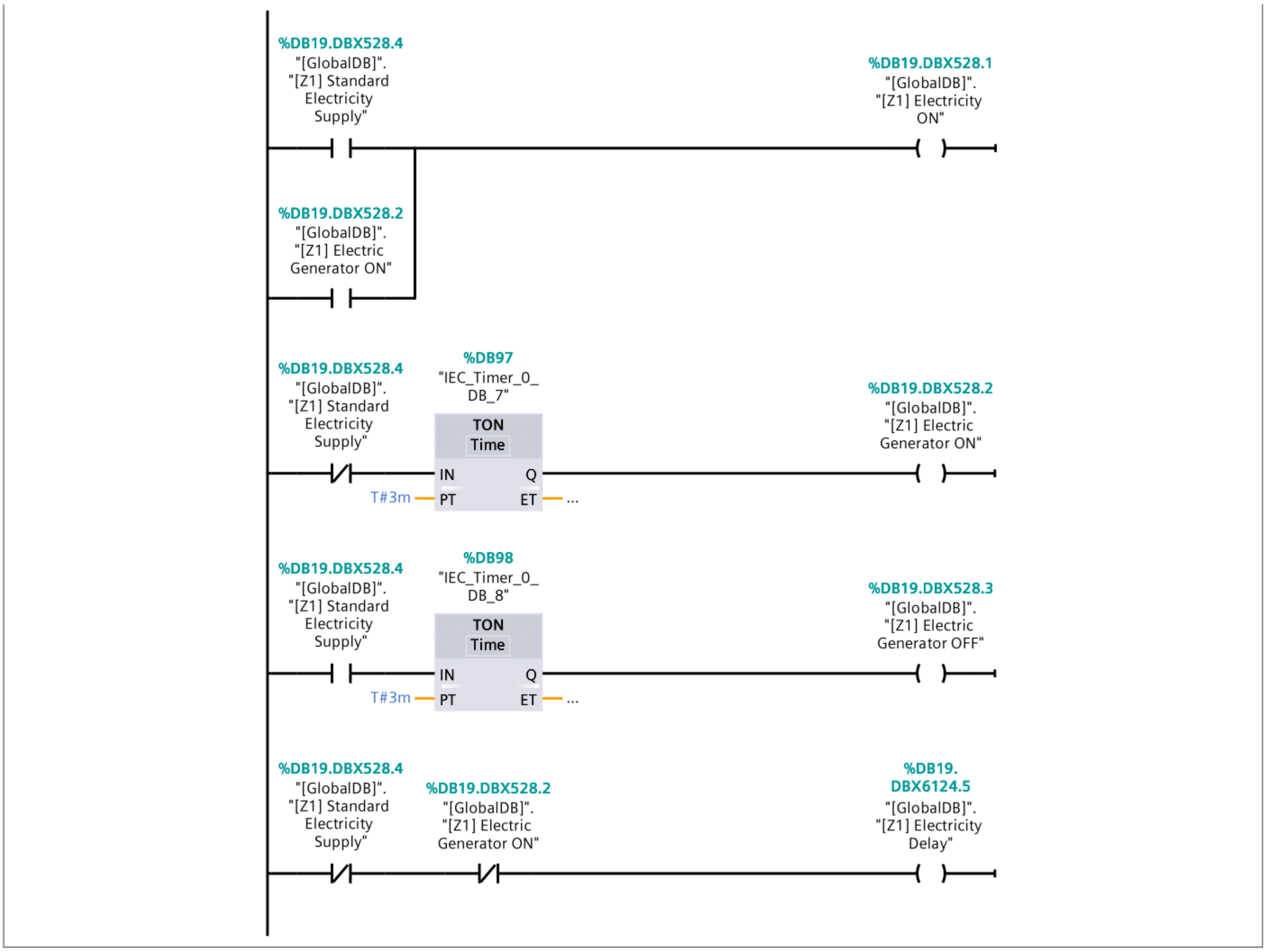
Network 1:



Network 2:



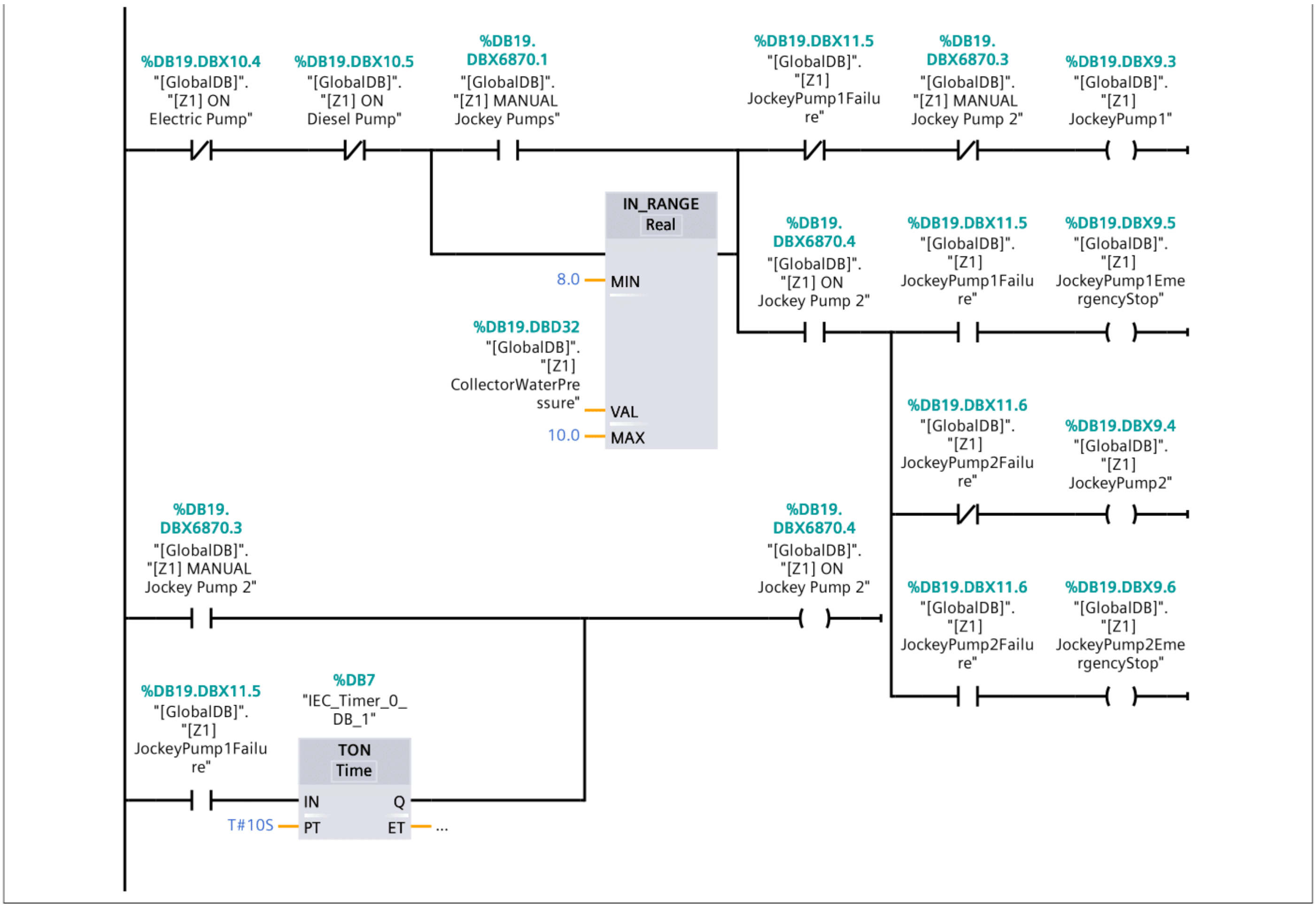
Network 3:



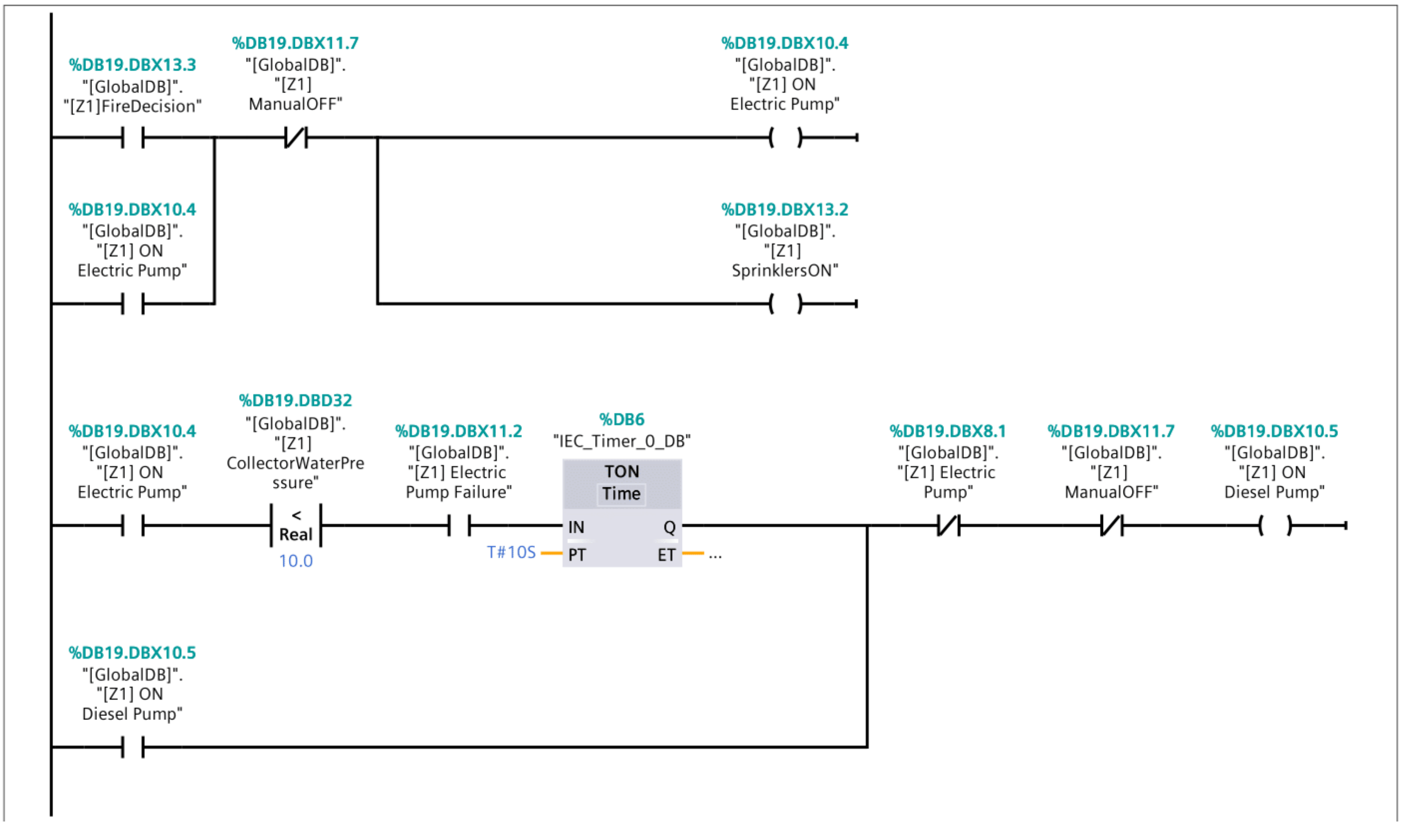
Network 4:

Network 5:

Appendix E

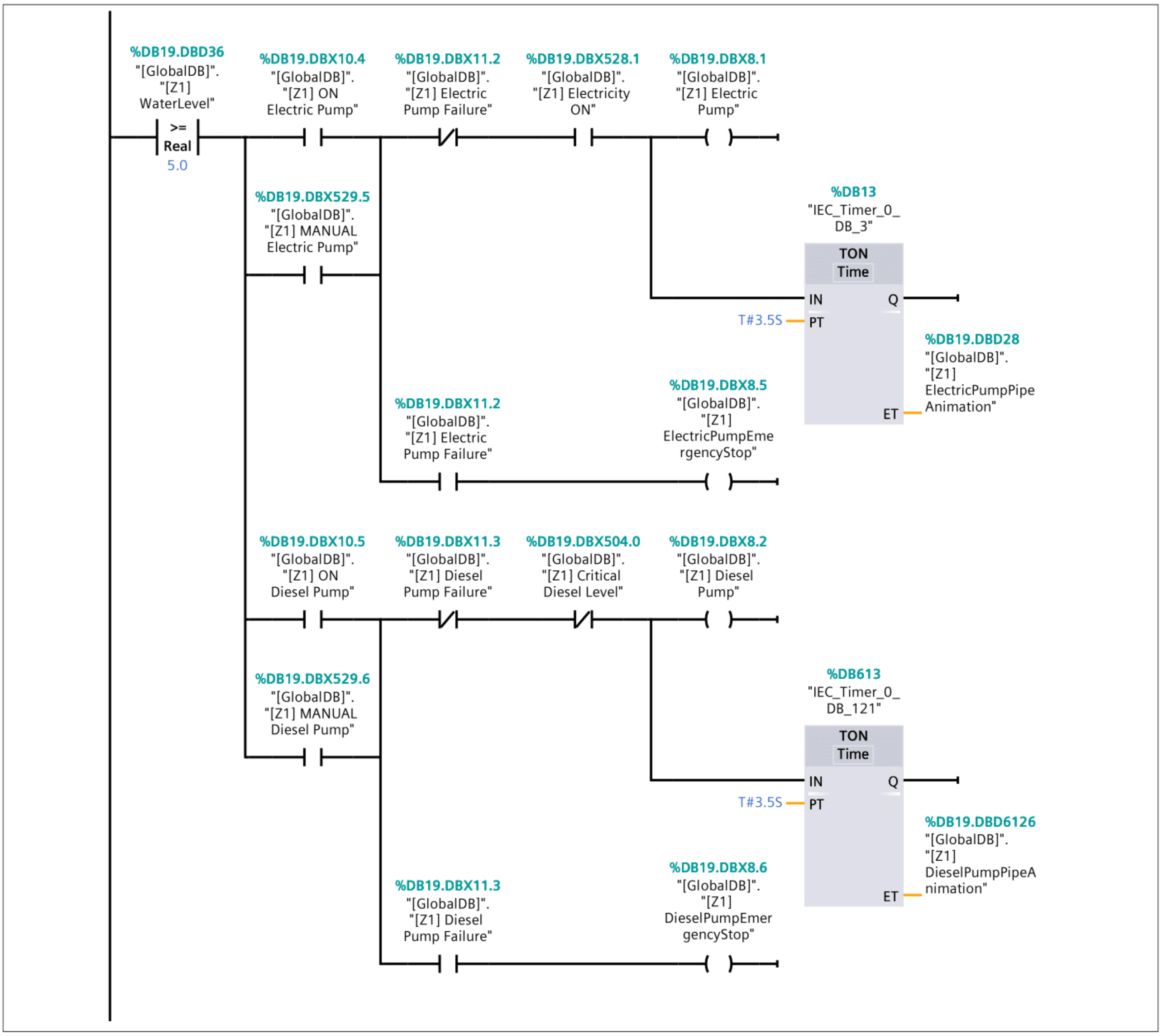


Network 6:

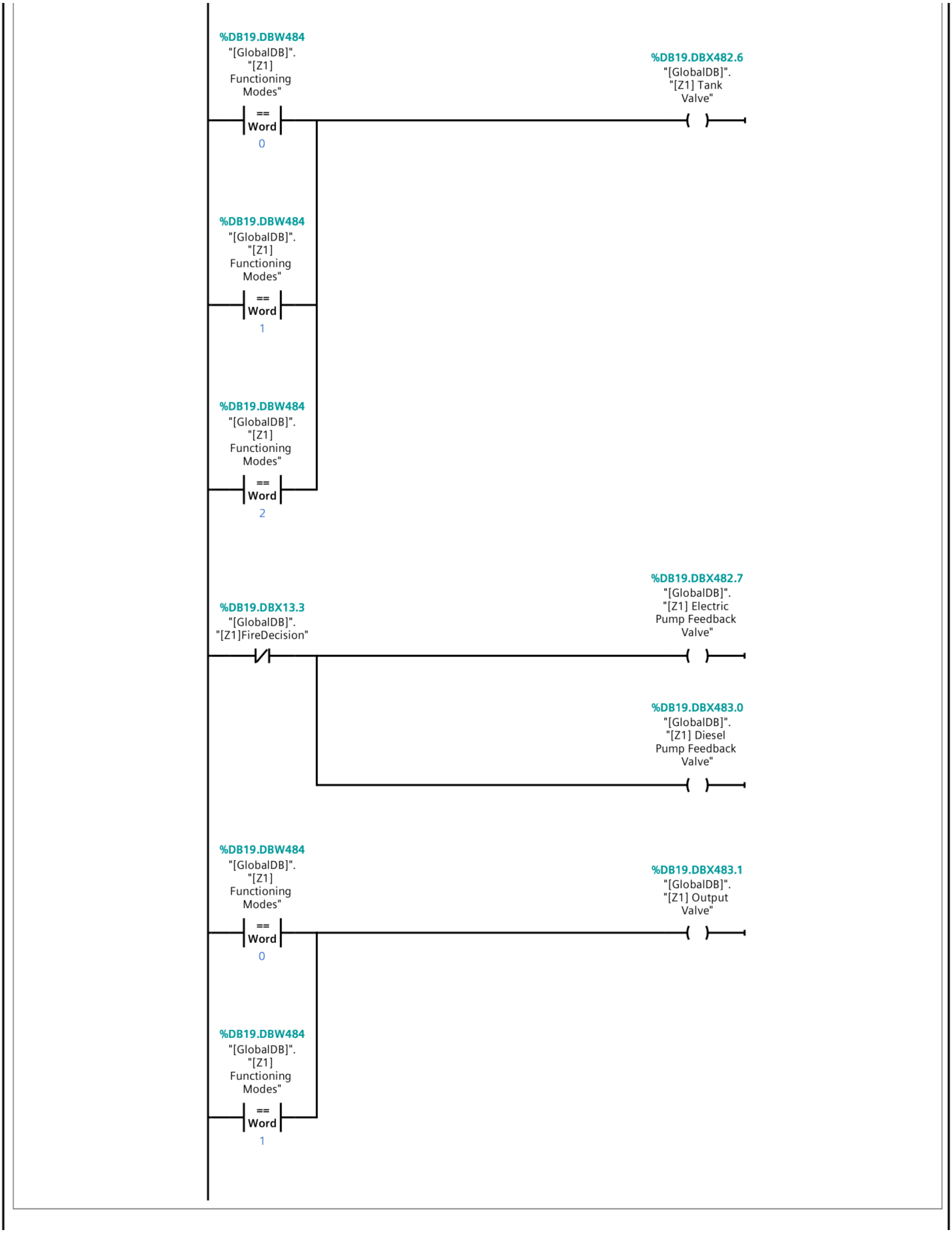


Appendix E

Network 7:



Network 8:


%DB19.DBW484
"[GlobalDB]".
"[Z1]
Functioning
Modes"
==
Word
0
%DB19.DBX482.6
"[GlobalDB]".
"[Z1] Tank
Valve"
%DB19.DBW484
"[GlobalDB]".
"[Z1]
Functioning
Modes"
==
Word
1
%DB19.DBW484
"[GlobalDB]".
"[Z1]
Functioning
Modes"
==
Word
2
%DB19.DBX13.3
"[GlobalDB]".
"[Z1]FireDecision"
%DB19.DBX482.7
"[GlobalDB]".
"[Z1] Electric
Pump Feedback
Valve"
%DB19.DBX483.0
"[GlobalDB]".
"[Z1] Diesel
Pump Feedback
Valve"
%DB19.DBW484
"[GlobalDB]".
"[Z1]
Functioning
Modes"
==
Word
0
%DB19.DBX483.1
"[GlobalDB]".
"[Z1] Output
Valve"
%DB19.DBW484
"[GlobalDB]".
"[Z1]
Functioning
Modes"
==
Word
1