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CYBER-PHYSICAL SYSTEM FOR REMOTE MONITORING AND CONTROL OF A DRINKING WATER NETWORK

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ABSTRACT

The fundamental aim of this paper is to investigate and explore the design and simulation methods for a cyber-physical system (CPS) for the monitoring and control of drinking water capture, treatment and distribution processes. This research aims to provide a deep understanding of the theoretical concepts underlying CPS systems, as well as a detailed analysis of the technologies and methodologies used in the design and simulation of these complex systems.

Through this investigation, we aim to identify effective solutions for the management of drinking water resources, given the critical importance of water in modern society. By analyzing case studies and current practices, we will assess the advantages and challenges associated with implementing a CPS system in the real-world context of water supply infrastructure.

This work not only aims to provide a theoretical perspective on the concept of CPS applied in the field of drinking water supply, but also to contribute to the development and implementation of practical solutions in order to ensure universal access to quality water and to protect the environment. Through academic approach and rigorous research, we hope to make a contribution to the field of mechatronic engineering and environmental technologies.

Keywords: cyber-physical system, PLC, SCADA software

INTRODUCTION

Today, the technologies around us are not only tools we can use to improve our lives, but also powerful factors that influence our perception of the world, change our behavior, and shape what it means to be human. This perspective reflects an evolution in the way society interacts with technological innovations, transformed by the previous three industrial revolutions [1].

The first industrial revolution, beginning in the early 19th century, marked a significant transition from the use of human and animal power to the exploitation of mechanical energy and fossil fuels. This change has fundamentally shaped the way human activities have been organized and carried out, fundamentally influencing the way people interact with their physical environment.

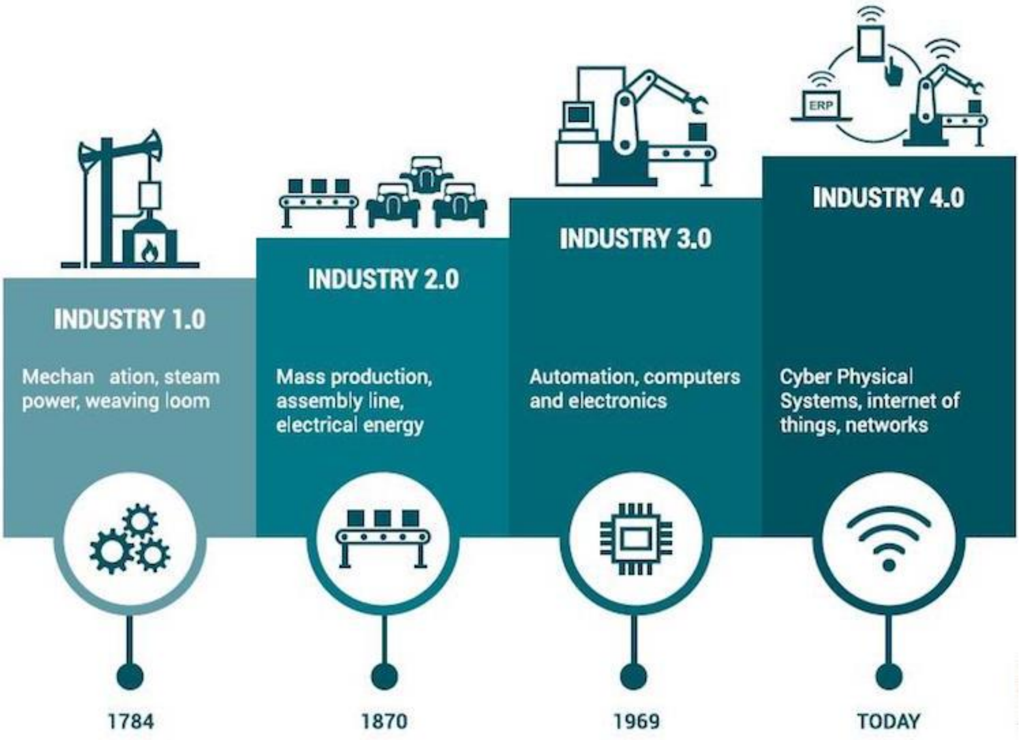

***Figure 1**. Industrial evolution* [2]

The Second Industrial Revolution, which took place in the late 19th and early 20th centuries, represented a major leap in technology, introducing significant innovations in electricity distribution, communications, and other aspects of human life. These advances have led to a deeper integration of technology into everyday life and have influenced the way people perceive and interact with their environment.

The third industrial revolution, which took place in the 1950s, was dominated by the advance of digital systems and communications, fundamentally changing the way we generate, process and propagate information. This transformation has accelerated the pace of technological change and strengthened the role of technology in everyday life, significantly transforming the way people relate to knowledge and interaction with their world.

The current fourth industrial revolution can be described as the emergence of "cyber-physical systems" that involve completely new capabilities for humans and machines. While these capabilities are based on the technologies and infrastructure of the Third Industrial Revolution, the Fourth Industrial Revolution represents entirely new ways in which technology becomes embedded in societies and even in our human bodies. Examples include genome editing, new forms of machine intelligence, innovative materials, and approaches to governance that rely on cryptographic methods such as blockchain.

Cyber-physical systems (CPS) are information systems that integrate computers, computing machines, communication systems and automated control systems to achieve the desired performance of physical processes as defined by ENISA (European Union Agency for Cybernetics).

In Romanian legislation, the concept of Cyber-Physical Systems is defined as "integrated systems in which physical parts and processes are controlled by algorithms or software", according to Annex no. 3, Acronyms and abbreviations, annexed to Government Decision no. 429/2019, which approved the 5G Strategy for Romania, dated June 20, 2019.

CPSs have become some of the most computerized applications today, providing abstractions and techniques for modeling, design, and analysis. These and other emerging technologies have become essential pillars of critical infrastructure, governance and everyday life. From automobiles and medical devices to building security systems and smart sensor networks, CPSs integrate smart devices, sensor networks, and processors to interact with the physical environment and provide real-time performance in critical applications and security. Emerging technologies include artificial intelligence, quantum computing, the Internet of Things (IoT), blockchain, advanced biotechnology, and autonomous vehicles. These technologies have the potential to transform various aspects of human life and the economy, but often require time and resources to be fully developed and adopted [5, 6].

However, the use of CPSs also brings major cybersecurity risks, impacting people and the environment. It is imperative that both citizens and specialized institutions work to strengthen security and trust in these emerging technologies.

It is essential that we focus not only on the widespread implementation of CPSs, but also on the continuous resolution of cybersecurity issues from the early stages of systems design and implementation. Communicating and sharing security findings is fundamental to strengthening existing systems.

CPS STRUCTURE

The structure of a CPS (Cyber-Physical System), shown in figure 2, involves the harmonious integration of cyber and physical elements into a coherent and functional system, capable of interacting with its environment. This integration is achieved through several distinct components, each with its specific role in the operation and performance of the system. The first element of the structure of a CPS consists of the physical components, which represent the material entities of the system. These may include sensors, actuators, mechanical devices or other physical objects that interact directly with the environment and collect relevant data [2, 3].

In parallel, cyber components form the digital part of the CPS. These include computing and communication elements such as microcontrollers, processors, communication modules and associated software. These components enable data processing, decision making and communication between different parts of the system.

A CPS also includes control software, which is the set of algorithms and programs that regulate and coordinate the operation of the CPS. These programs can perform various operations such as process control, data analysis or system performance optimization.

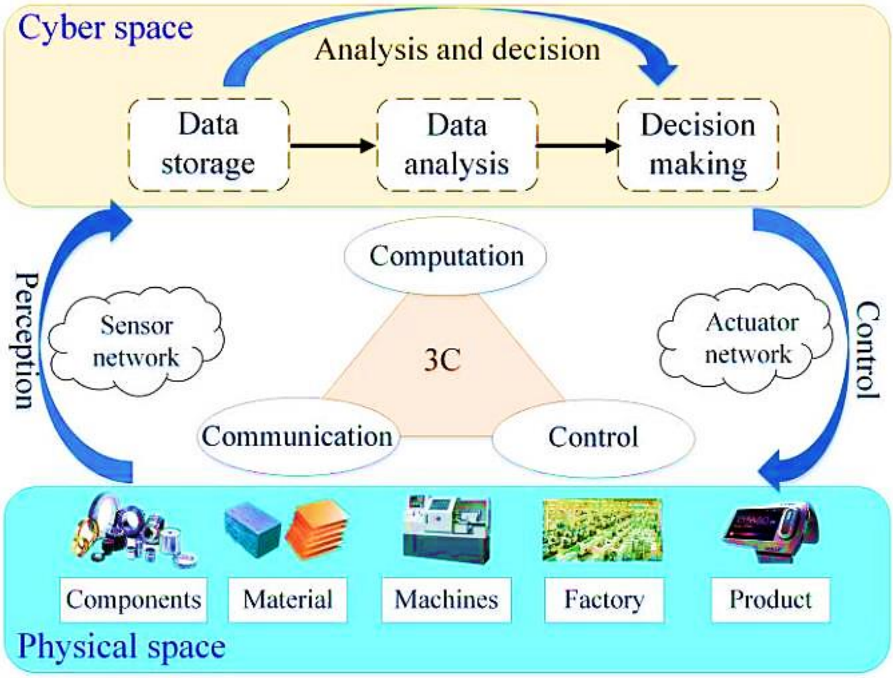

Figure 2. *Structure of a CPS* [2]

DESIGN OF A CYBER-PHYSICAL SYSTEM FOR A DRINKING WATER NETWORK

The structure presented in Figure 3 shows a systematic organization of the "Cyber" and "Physical" components and the interactions between them. By dividing it into distinct blocks, the system becomes easier to understand and manage, allowing for efficient monitoring and rapid intervention in case of need. The following aspects will be dealt with: capture, treatment, accumulation and distribution of drinking water.

This modular structure facilitates the implementation and optimization of each component, contributing to a more fluent operation and achieving the desired results in drinking water management [7, 8, 9].

- **"Cyber" Components**
    - **Command and monitoring center:** The interaction takes place predominantly in the digital environment, where data is collected, processed and monitored in real time. This block manages the information flow and provides a control interface for operators.
    - **Data acquisition system from the distribution network:** This component is responsible for collecting data from the distribution network and transmitting it to the command and monitoring center. Data is digitally processed for analysis and decision making.
    - **Mobile SCADA Client:** It is a digital interface through which users can monitor and control the system remotely, using mobile devices or computers connected to the Internet.
    - **Internet connection via VPN:** It provides a secure connection between the various system components and allows data access and remote system control through a virtual private network.

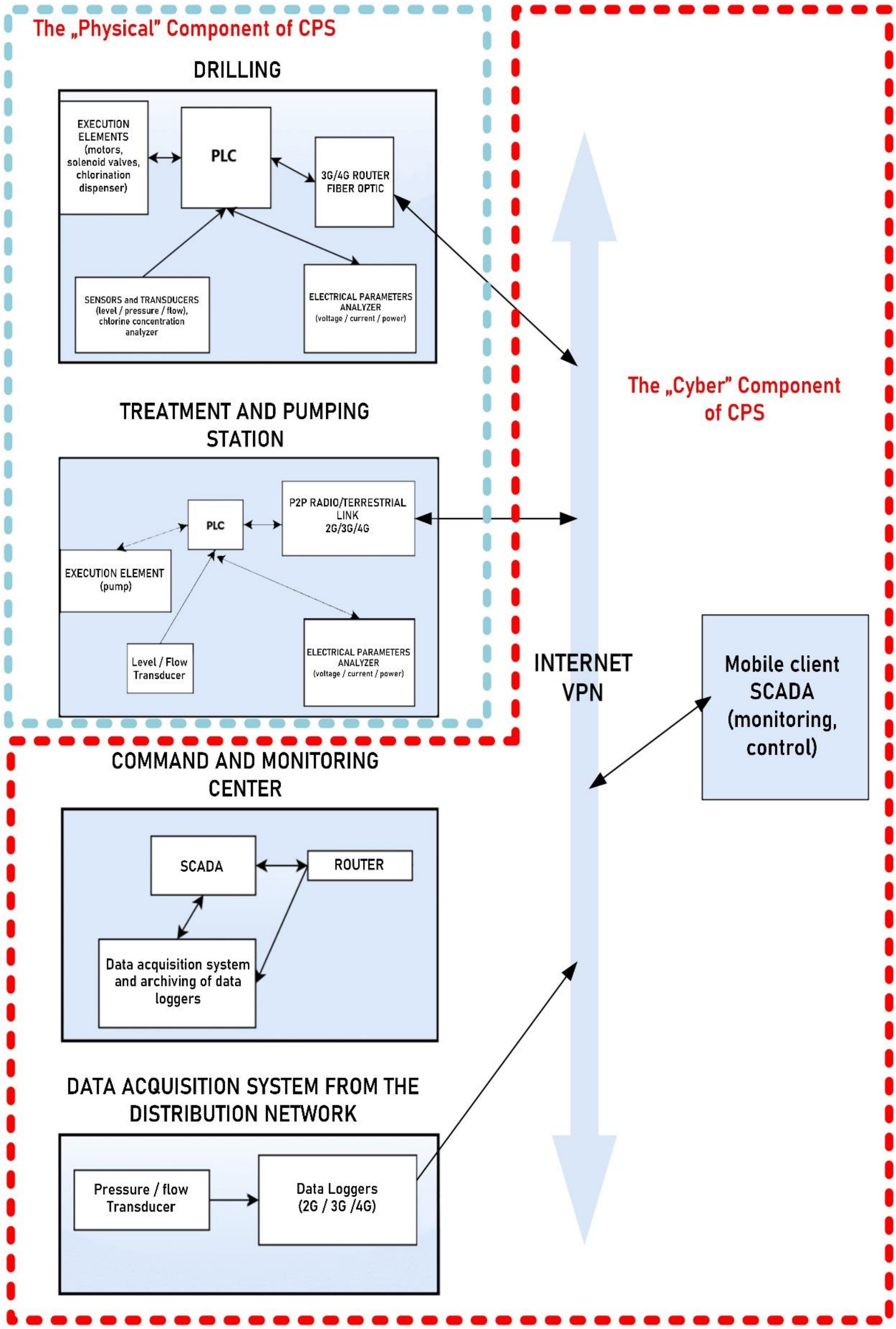

Figure 3. *Hierarchical cyber-physical system structure for remote monitoring and control of a drinking water collection, treatment, storage and distribution system* [10]

- **Physical Components:**
  - **Drilling:** These are the physical points from where the water is extracted. It includes pumps, level and flow sensors and other equipment needed to extract water from the ground.
  - **Pumping and treatment station:** A physical facility that deals with pumping water from boreholes, treating it and preparing it for distribution. The block dedicated to the borehole catchment front is an essential element of a complex water management system. Here is an academic level description of each component:

The "physical" system: execution elements, transducers, parameter analyzers

The physical system represents the tangible infrastructure of the entire process, including the capture front, the transmission network, the treatment and pumping system in the distribution and the distribution network itself.

The capture front represents the set of wells that serve the system. Each well is equipped with an electrical panel intended to supply and control the execution element, in this case, a submersible pump.

The transport network represents the physical connection between boreholes, through which the raw water is transported to the treatment and pumping station for distribution.

The treatment and distribution pumping station consists of a raw water pre-treatment system from the transport network, an intermediate tank intended for the accumulation of pre-treated water, a distribution pumping group and a water post-treatment system that ensures the quality of water to end users, according to the standards imposed by the regulations in force [4].

The distribution refers to the entire network of pipes that branch off from the main pipe at the outlet of the pumping station. This network comprises the primary bus, branches and branches that extend to the end users. Thus, the distribution has the role of delivering water efficiently and safely to the various destinations, covering the diverse needs of the community or the area served.

"Cyber-physical" system: PLC / Data Loggers / data communication network

The cyber-physical system is an advanced integration of technological components that act synergistically to control and monitor various processes such as raw water production, drinking water treatment and distribution. This system consists mainly of command and control equipment, known as programmable logic controllers (PLCs), which form the heart of the system, ensuring the coordination and execution of programmed functions.

In parallel, smart sensors and transducers add a level of intelligence and adaptability to the system. They constantly monitor parameters such as the water table level (in the case of drilling, using level relays avoids the situation in which the submersible pumps would work empty), the level in the intermediate tank (by using an ultrasonic or radar level transducer, the PLC in the station of treatment and pumping commands the start or stop of the wells), the flow of water from the exit of the wells, the entrance and exit of the treatment and pumping station (by using, for example, electromagnetic flowmeters) and the pressure (for example, by using the pressure transducer located at the exit treatment and pumping station, the PLC, using specific automatic regulation algorithms such as PID, controls the frequency converters to maintain a predetermined pressure in the distribution network).

Also part of the cyber-physical system are the electrical parameter analyzers, having the role of evaluating and managing the electrical aspects of the entire system. These sophisticated devices allow accurate and detailed measurement of various electrical parameters, contributing significantly to optimizing consumption and preventing potential problems or breakdowns, thus reducing maintenance costs and downtime.

By constantly monitoring active, reactive and apparent voltage, current and power, the analyzers provide a detailed understanding of the electrical behavior of the system.

The voltage is evaluated to ensure that it falls within specific limits, thereby preventing equipment damage and ensuring operational safety.

The current is measured to identify the actual consumption and to prevent possible overloads that can lead to equipment failure.

Data acquisition from sensors and transducers that provide only a single process variable is typically done using the 4-20 mA current loop. In the case of equipment with a complex functionality that requires the purchase of several process variables (for example, flow meters that provide as process variables both the instantaneous flow rate and the totalizer of the water volume) or where the communication between the equipment is bidirectional (for example PLC <-- -> frequency converters), data exchange is done through serial communications (for example Modbus RTU) or ethernet (with Modbus TCP, Ethernet/IP or PROFINET protocols as examples).

Network equipment such as routers are essential components for connectivity and communication between the various elements of the cyber-physical system. They facilitate fast and secure data transfer between PLCs and smart devices, ensuring efficient information integration.

Data loggers are tools that record and store system parameter data for later analysis. In the event of failure or unusual behavior, they provide historical information essential to understanding and diagnosing the causes. This aspect allows operators to implement corrective and preventive measures, helping to avoid major breakdowns in the future.

The cyber-physical system would not be complete without the communication infrastructure, which includes specialized communication devices (modems / media converters). They allow the transmission of essential information between the various components, ensuring coherence and synchronization in the operation of the system. Through the integration and cooperation of these components, the cyber-physical system demonstrates an advanced approach to the management and control of technological processes. It not only optimizes operational efficiency, but also improves the ability to adapt to various changes and demands, thus contributing to the continuous evolution of modern technology [4].

"Cyber" system: SCADA / VPN / internet

The cyber system materializes through the SCADA application, an application that facilitates the monitoring and control of industrial processes. SCADA, short for Process Control and Supervisory System, is the backbone of this system, allowing operators to monitor and manage the status of equipment and processes within a complex system. Using intuitive graphical interfaces, operators have the ability to monitor equipment status in real time and intervene in processes to make immediate decisions. This ability for direct control and interactivity gives operators considerable power over the system, contributing to the efficiency and optimal operation of the entire serviced system.

Together with the mobile SCADA client, which extends access to information and control to portable devices, the cyber system becomes more flexible and adaptable to the needs of field operators. Through the use of real-time information, taken by the SCADA system from the intelligent equipment in the field, a continuous and detailed monitoring of the state of the transmission network and the primary distribution network is achieved.

For example, by monitoring flows in real time, SCADA system operators can detect unexpected variations that could indicate anomalies (breakdowns) in the transmission network or the primary distribution network. In the case of secondary distribution networks, by using the information provided by the data loggers, anomalies in the operation of these networks can be identified in a timely manner. At the same time, the ability of the SCADA system to extract and analyze data from previous periods is a valuable tool in resource management, offering users a more comprehensive perspective and contributing to the efficiency and reliability of execution, monitoring and control systems.

SIMULATION OF A CYBER-PHYSICAL SYSTEM

Simulating the operation of a cyber-physical system for remote monitoring and control of a drinking water collection, treatment, storage and distribution system is an effective way to evaluate its performance and reliability in a controlled environment. By using computer and algorithmic models, simulation reproduces the behavior of the system under various conditions and scenarios, allowing engineers and operators to understand its operation and identify possible problems or improvements.

Through simulation, different system configurations can be tested, control algorithms can be optimized, and responses to emergencies or anomalies can be evaluated. This process enables informed decisions to be made regarding the design, implementation and operation of the drinking water system, contributing to water quality assurance and resource efficiency.

In addition, simulating the operation of the cyber-physical system provides the opportunity to train personnel and develop crisis intervention procedures, helping to increase the skills and training of the operating team. By integrating technology and advanced simulations, it can ensure the optimal operation of the system and meet the needs of the community in terms of access to safe and reliable drinking water.

Figure 4 shows the simulated structure of the cyber-physical system for remote monitoring and control of a drinking water collection, treatment, accumulation and distribution system. Through this integrated solution, the aim is not only to provide drinking water continuously and efficiently, but also to optimize the monitoring and control processes, so as to ensure proper operation and proper maintenance of the entire system.

This system is divided into the following components: boreholes; storage tank; distribution pumping group; automation and actuation; communications; dispatched SCADA (supervisory control and data acquisition). Next we will go through each component separately to understand how this CPS works.

DRILLING

Submersible pumps are used to capture and pump water from boreholes. The water level in the boreholes is monitored by means of level electrodes and one level relay each (named **LR1** and **RL2**). These level electrodes, together with the level relay, ensure the proper operation of the wells between the two levels, **E1** and **E2**.

The pumps of the two boreholes are turned off when the water level reaches electrode **E1** and are restarted only when the water level reaches electrode **E2**. In addition, protection against lack of water is provided for the two pumps. Flow meters are mounted on the discharge of the borehole pumps to measure the amount of water pumped into the tank.

To monitor the three-phase power supply, phase monitoring relays (**PMR1** and **PMR2**) are installed that provide protection against phase failure, phase asymmetry, overvoltage and undervoltage. The information related to the level, flow rate and electricity supply is managed by one PLC (**PLC1** and **PLC2**), which communicates, through a **GSM** router+modem, with the SCADA application, installed on the server in the control room, and with the water tank.

ACCUMULATION TANK

The tank has a capacity between 150 m^3 and 1000 m^3 and has the role of accumulating water. The monitoring of the water level in the tank is provided by an ultrasonic level transducer which is connected to the analog input (4-20 mA) of a PLC (**PLC3**).

The lack of water protection of pumps **P3** and **P4** in the distribution network is ensured by a level relay (**N-WR**). Monitoring of the three-phase power supply is provided by a phase monitoring relay (**PMR3**) which provides protection against phase failure, phase asymmetry, overvoltage and undervoltage and is connected to PLC3 at analog input **I0**.

Information about level, lack of water and three-phase power supply is managed by a local PLC (PLC3). When the water level in the tank reaches a minimum set value, the PLC (PLC3) sends the water request command, implicitly requesting the start of the well pumps, to the two PLCs (PLC1 and PLC2) that manage the operation of the wells. When the maximum level in the tank is reached, the stop command is sent to the two pumps via the two PLCs (PLC1 and PLC2). At the same time, information about the level, lack of water, electricity supply and the status of the pumps is transmitted via the Internet to the SCADA application from the Dispatch.

PUMPING GROUP IN DISTRIBUTION

The pumping group in the distribution must ensure a constant pressure in the network. It consists of two pumps, **P3** and **P4** driven by a frequency converter. The frequency converter operates with a variable frequency, ensuring a variable flow to maintain a constant pressure in the network. The pumps are fed from the storage tank. A pressure transducer (**PT**) is installed on the output circuit which reads the pressure and sends the information to a PLC (**PLC4**).

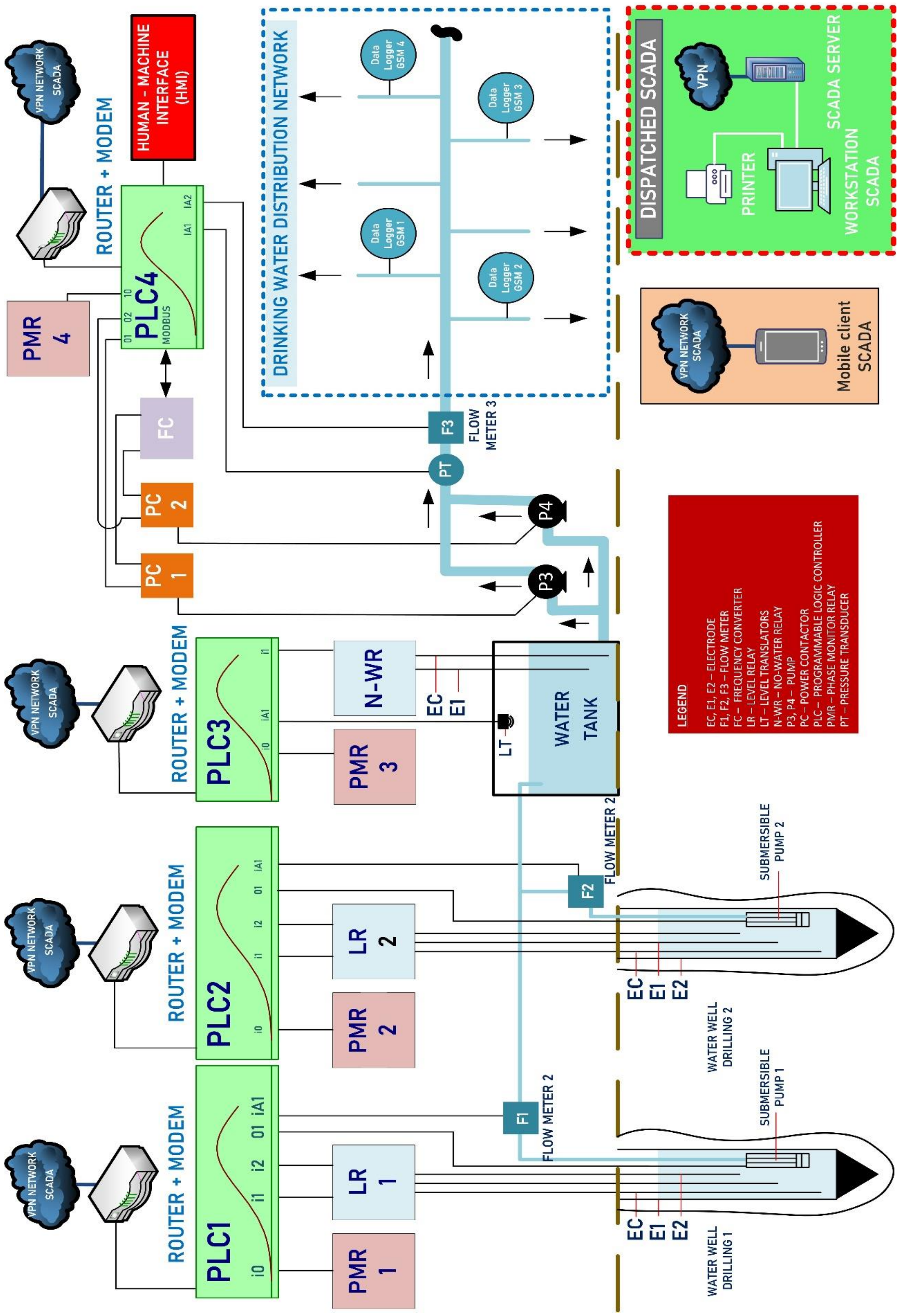

Figure 4. *The structure of the cyber-physical system used in the simulation* [4]

AUTOMATION AND ACTUATION

The automation of the capture, storage and distribution pumping system is managed by a number of 4 PLCs, together with peripheral equipment, sensors, transducers, actuators and communications. PLCs have digital and analog inputs and analog and digital outputs with relays or transistors. The level relays RLN1 and RLN2 monitor the water level in the boreholes to prevent the pumps from running out of water and failing. The level relays transmit the information to PLC1 and PLC2 at inputs I1 – I2.

Flowmeters D1 and D2, either electromagnetic or ultrasonic, are installed on the output (discharge) circuit of the two wells and transmit the information to the analog inputs IA1 of PLC1 and PLC2. Outputs O1 of PLC1 and PLC2 command, by means of power contactors, the start and stop of the boreholes according to the water demand of the tank. The **LT** level transducer can be ultrasonic or hydrostatic and has the role of measuring the water level in the tank and transmitting the analog information (4-20 mA) to PLC3 at the analog input IA1. The RLLA relay provides the protection of the pumping group P3 and P4 for lack of water in the tank and communicates the information to the digital input I0 of the PLC3.

Monitoring of the three-phase electricity supply to the distribution pumping station is provided by a phase monitoring relay (RMF4) which provides protection against phase failure, phase asymmetry, overvoltage and undervoltage and is connected to digital input I0 of PLC4.

The CF frequency converter ensures the operation of the P3 or P4 pump with variable frequency and implicitly with variable speed, therefore variable flow. The pressure transducer is installed on the discharge circuit of the two pumps P3 and P4, it reads the water pressure in real time and transmits the information to PLC4 at the analog input IA1. The PLC communicates with the CF converter via the MODBUS protocol. The two power contactors PC1 and PC2 connect one of the two pumps P3 or P4 to the converter. The contactors are controlled by outputs O1 and O2 of PLC4. Also on the discharge circuit is installed the flow meter D3 which counts the volume of water to the distribution network and is connected to the PLC at the analog input IA2. An HMI (human machine interface) is connected to the PLC to view the parameters in the system and to operate the drive equipment locally. The HMI has a touch screen display that shows information in real time and virtual buttons for operating the pumps.

For efficient system management, GSM data card loggers can be installed along the distribution network route that transmit real-time pressure and/or flow information to the SCADA. These loggers are powered by batteries or accumulators and, to conserve energy, transmit the accumulated data over a set period and at set intervals, only once a day.

COMMUNICATIONS

Communications are handled by industrial devices such as routers/modems. Information is transmitted to the SCADA dispatcher over the Internet, using a VPN tunnel to ensure data security. At the pumping station and dispatching, GSM or fiber optic connections can be used for data and communications.

SCADA DISPATCHER

The SCADA dispatcher consists of a server running the SCADA application, a computer and a printer. SCADA software allows monitoring, data acquisition and remote control of pumping station equipment. It is installed on a server where data is collected and commands can be sent. For the actual control of the application, a local PC or mobile device is used that connects to the SCADA server via the Internet. The printer installed at the PC in the SCADA control room is required for listing events, graphs, etc.

EXPERIMENTAL RESULTS

Figure 5 shows the graphic interface of the cyber-physical system in the field of industrial mechatronics, for remote monitoring and control of a drinking water collection, treatment, accumulation and distribution system.

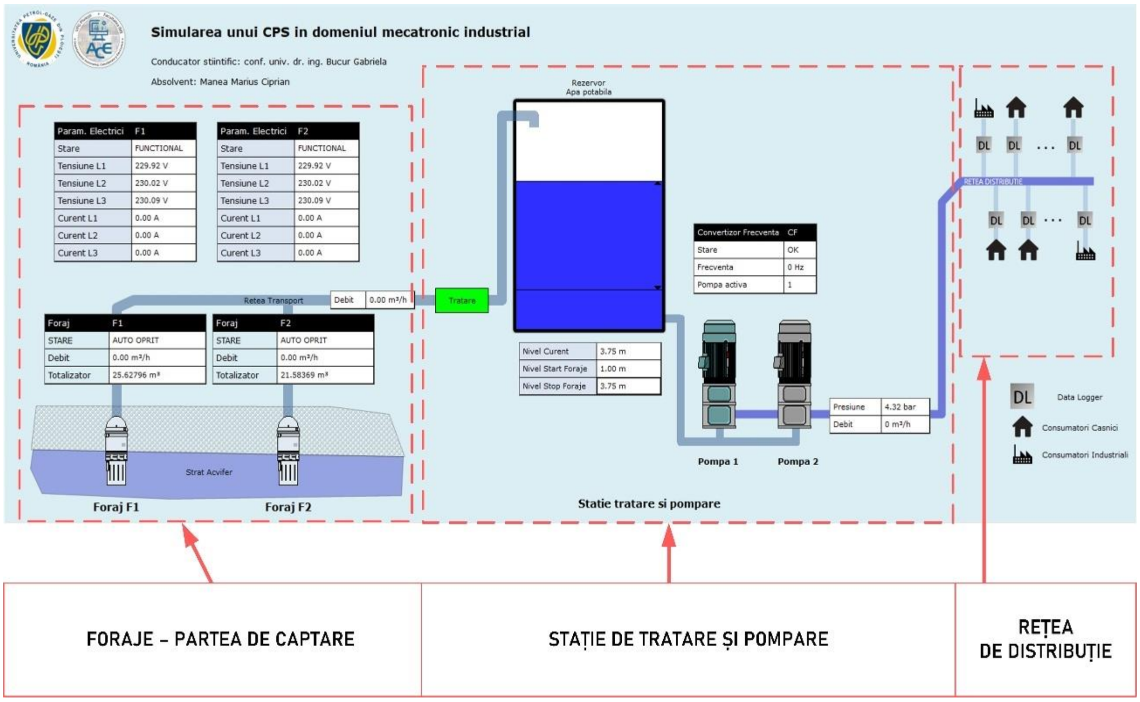

Figure 5*. Graphical interface of the designed cyber-physical system* [4]

It shows the three areas: capture, treatment and pumping, and the distribution network.

The following can be changed in the graphical interface:

- drilling pump states: AUTO, OFF / ON;
- level START / STOP drilling, at the tank;
- distribution pressure setpoint.

These changes can be made in normal system operation.

In the graphic interface, you can monitor data such as flows from the pumps and from the transport and distribution network, reservoir water level, pressure in the installation, the electrical parameters of the pumps and the states of the equipment, shown in figure 6, which represents a normal operation of the entire system.

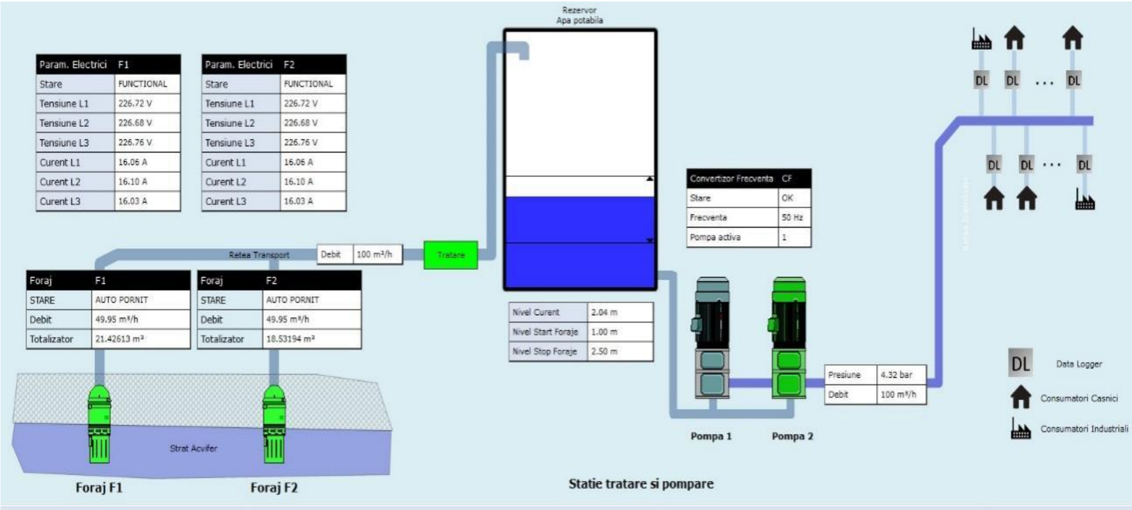

Figure 6. *Normal system operation*

A suggestive representation for a normal operation is shown in figure 7, where the data graphs of the borehole flow rates, the flow rate entering the treatment and pumping station, and the reservoir level are displayed.

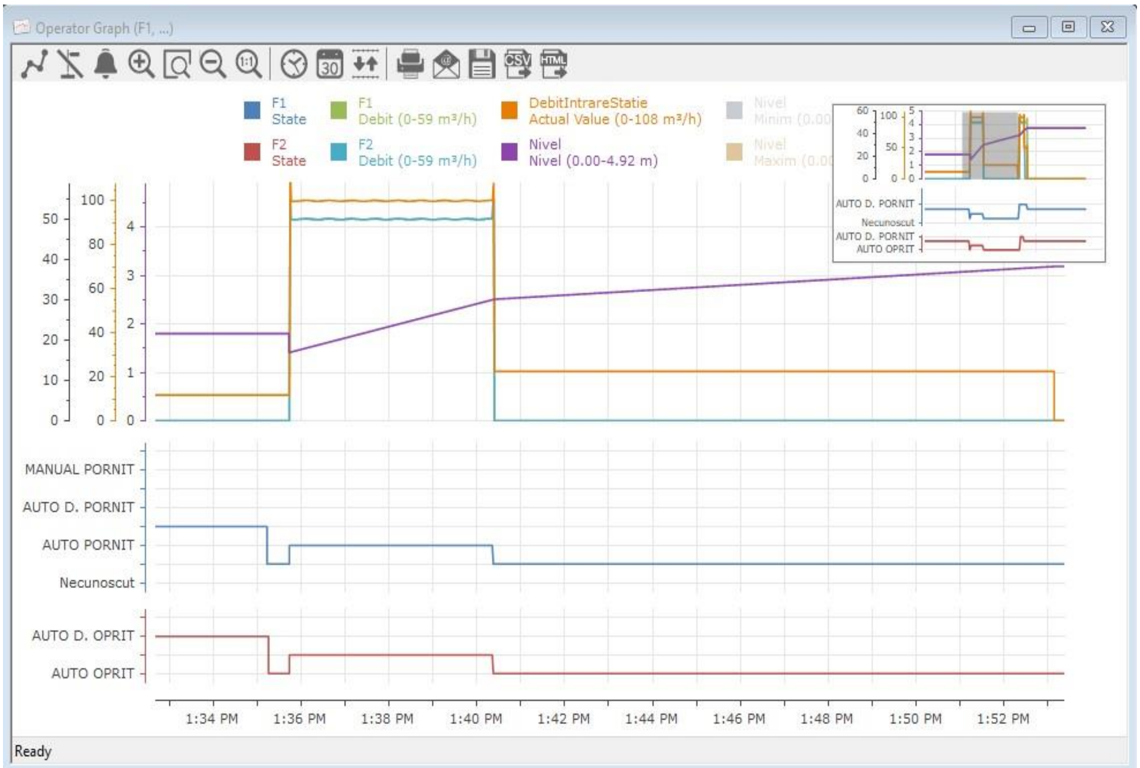

Figure 7. *Chart of normal system operation*

It is observed that the level in the tank has fallen below the set minimum level and the command to start the well pumps has been given to restore the set maximum level. The flow of the two pumps summed the flow at the station inlet, indicating that there is no loss along the route. At the end of the graph it can be seen how the maximum reservoir level has been reached and the well pumps have stopped.

A situation was simulated in which the submersible pump of borehole 2 stopped due to electrical faults (a power supply phase was missing) and the SCADA operator intervened shortly by stopping the pump of borehole 1 to check the causes of the fault.

This can be seen in the graphs below, namely figure 8, figure 9, figure 10 and figure 11. The graphs are in chronological order to highlight the moments of each stage of operation up to the time of failure and shutdown of well pump 1.

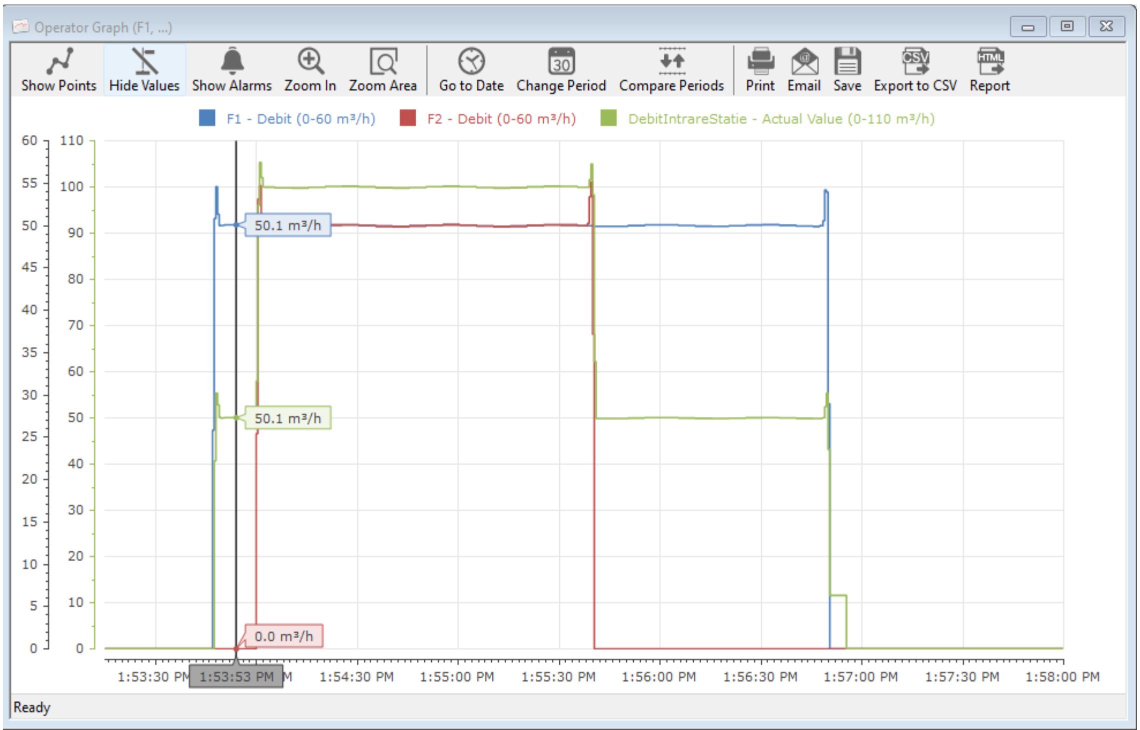

Figure 8. *The moment of starting the well pumps*

In this graph it can be seen how the two pumps start and both operate at maximum flow, respectively 50.1 m3/h.

The graph in figure 9 shows how the pumps work normally and the flow at the entrance to the treatment and pumping station indicates the sum of the flow values of both pumps.

In the graph in figure 10, it can be seen how the pump of well 1 has stopped and the flow is decreasing.

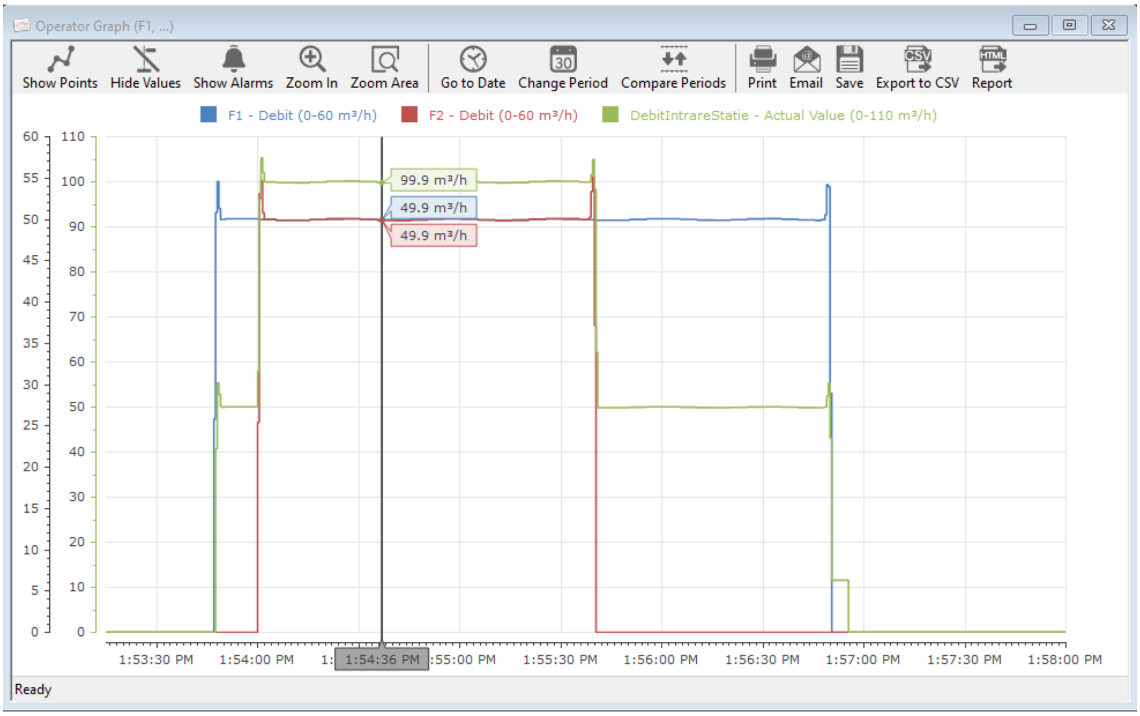

Figure 9. *Graph of normal operation of well pumps*

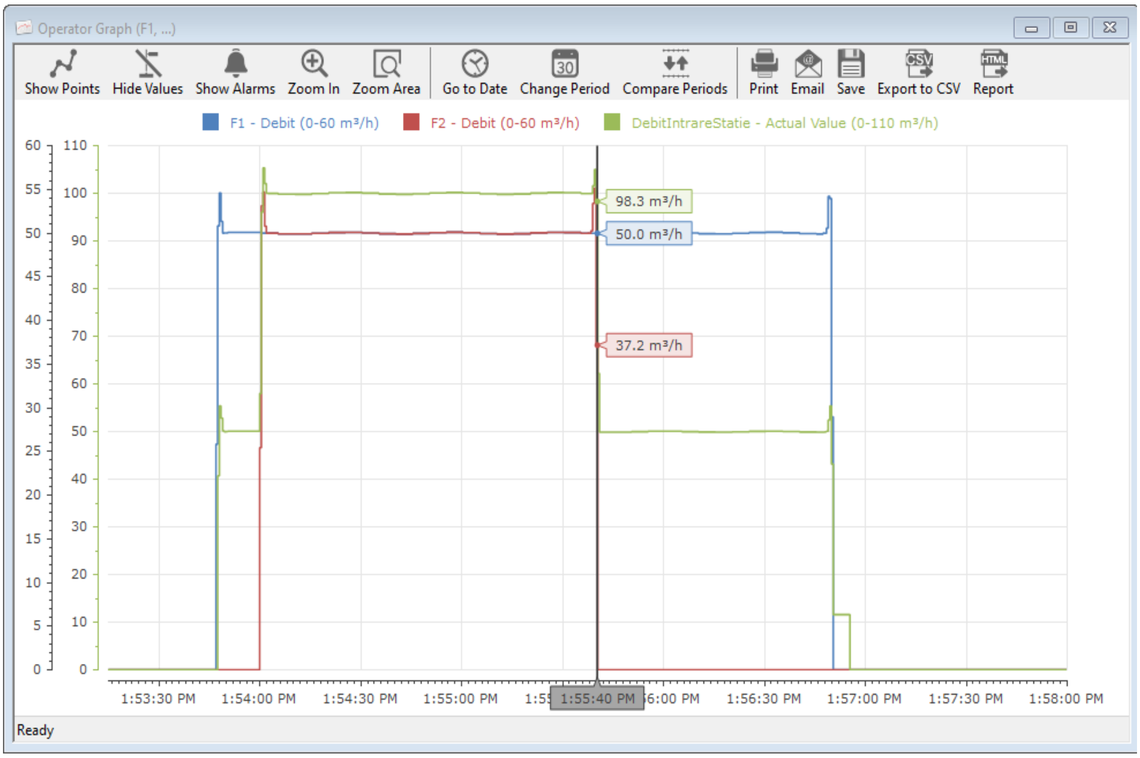

Figure 10. *The moment of stopping the well pump 2*

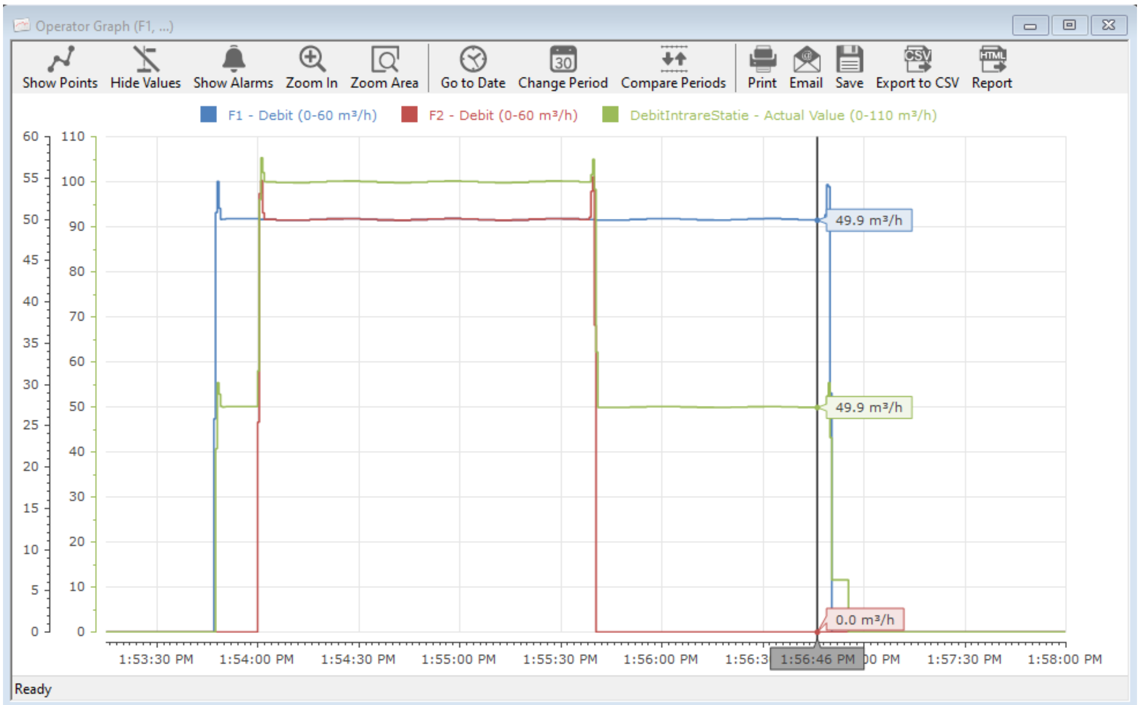

***Figure 11**. Time of SCADA operator intervention to stop borehole pump 1*

The graphic in figure 11 shows how the operator intervenes and stops the well pump 1 in order to investigate the problem of the electrical supply installation.

The display of graphs in IGSS provides a visual insight into the operation of the system and the evolution of various parameters in real time. By means of these graphs, the behavior of the pump, flow variations and other relevant aspects for process monitoring and control can be followed. The graphs allow operators to quickly identify any anomalies or changes in system operation, make informed decisions and optimize operational efficiency. Graphs can also be useful for analyzing data for diagnostic purposes and improving system performance.

CONCLUSIONS

To improve Cyber-Physical Systems (CPS), it is essential to advance the general perception and recognition of CPS technology. To achieve this, we need a deeper understanding of the integration of real-time processing with embedded wireless networks working in harmony with a variety of sensors in a dynamic physical environment. It is also crucial to investigate in depth the interactions between the cyber world and mechanically fabricated devices. We need efficient sensing and control of physical systems, achieved through a solid software architecture.

There are numerous challenges to address. Managing the random events that can occur in a real environment can be difficult for a CPS when trying to ensure safety, security and predictability. Through the concept of predictability, we can achieve precise timing and timing. Ensuring that a CPS operates in real-time in all operations can be complicated, considering the delay in the processing of data by the sensors until the action taken by the actuators. Remodeling or designing a system and keeping costs within a certain range are also priorities. System architectures must remain consistent for large-scale designs and protocols. Model-driven development, certification and verification of CPSs, network autonomy, and scalability of embedded systems are all issues that require attention and resolution.

CPSs will one day redefine how people interact and connect with the physical world. Efficient energy sources, advanced agriculture, high-performance health systems and secure systems will be realized based on CPS design principles.

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