MODEL-BASED METHODOLOGY FOR DESIGNING AUTOMATED WORKPLACES

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The article deals with model-based methodology for designing automated workplaces with control systems using programmable logic controllers. A categorization of some development methodologies and simulations of automated system control is presented. In the case study, a model of the controlled system is created, which is used for control simulations of the designed control system. The developed control system can thus be tested on this model, and any failure will thus only indicate possible errors in the control program or in the control hardware. Accordingly, it is then possible to modify the control system without the risk of possible damages or disasters. With this methodology, it is possible to implement control system training, especially in the case of dangerous and risky applications.

KEYWORDS

Pressure sensor, gauges, uncertainty, calibrator

1 INTRODUCTION

The process of designing a technical system, which is supported by a model of the system (English model-based design), makes it possible already at the early stage of the process of designing a technical system to reveal the weak points of the system and to debug it so that the goal is achieved as quickly as possible - fast and low-cost product development. The system model is thus the center of the system design process, from the requirements arising from the assignment of the task, through the design and implementation of the system itself, as well as the testing of the designed system. It is the simulations on the system model that will show whether this proposed system will work correctly. Model or technical system models have an important position in the process of developing a technical system. In this process, a system model is used to define workable specifications. Ongoing flexible testing during the development process will allow critical errors to be caught even before the actual implementation of the hardware. In this process, error tracking is easier, and interventions and changes are directly reflected in the feasible specifications from the system model [Kelemen 2012 and 2014, Murcinkova 2013, Koniar 2014, Virgala 2014, Mascenik 2018 and 2020, Kuchar 2019, Ruzarovsky 2019, Tlach 2019, Blatnicky 2020, Oscadal 2020, Peterka 2020, Klarak 2021, Kot 2021, Lestach 2022].

This article deals with the design of control systems with Programmable logic controllers (PLC). These are industrial control systems that obtain information from sensors and subsequently implement logical operations or operations where they compare the desired value of a variable with the current one and implement an action intervention in the controlled system using actuators. PLC automata are designed to handle parallel control operations in real time and are resistant to electrical noise and vibrations and shocks that are very common in industrial environments. PLC systems are located in switchboards together with other electrical modules and are not normally accessible to ordinary users. To communicate with the user, PLCs are equipped with a human-machine interface (HMI), which allows the user to check the status of the controlled system and possibly intervene in the control process, if the situation in the controlled process requires it.

Training stations with PLCs (Fig. 1) were made for testing purposes. The designed training station allows simulation of the control system with real parts before its practical use with an expensive controlled system, where any error can cause huge economic losses and endanger human lives. However, the errors that occur during the experimental simulation at the training station will only warn us and show a weak point in the designed device or the designed control system with a PLC automaton. Also, the training station also allows you to simulate even abnormal situations that cannot be trained on real systems, such as extremely low temperatures, extremely high speeds, etc.

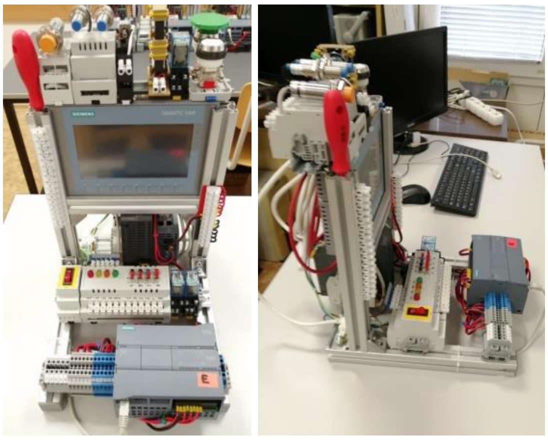


Figure 1. Training station with PLC

2 MODEL-BASED METHODOLOGY FOR DESIGNING AUTOMATED WORKPLACES

For the design of automated workplaces controlled by PLC or similar control systems, several methodologies can be used at different levels created by functions. The dominant role here is played by the simulation model of the controlled system (plant), which is used at almost every stage of the development of the control program.

2.1 *Software to User Simulation - Software simulation on a computer with manual software inputs*

The use of simulation of PLC systems within the software environment, in which a control program is developed where the inputs and outputs of the simulated PLC are implemented using simulation tables of inputs and outputs and the reaction of the system is monitored when the input values change (Fig. 2). The control program is run on a computer with a simulation program installed in a so-called virtual PLC, which to a certain extent imitates the behaviour of a real PLC very well. During the simulation, the simulation model of the HMI interface with additional buttons or switches or sliding adjustment elements (the so-called slide bar) or a process input field (I/O field) with the possibility of entering the numerical value of the input variable can be added, which can be used to set the values of the input variables. on the PLC inputs of the simulated model. Therefore, the user must manually activate the individual input variables of the program in the simulation table or by directly entering a specific variable (tag) into the memory address. Subsequently, it is possible to monitor the responses of the designed control program. With such a simulation, it is possible to test the control program even before the actual procurement of the PLC system. It is also possible to try such combinations of inputs, which in practice may not occur, but may occur in case of critical failure conditions. The disadvantage is that this type of simulation may not correspond to the actual behaviour of a real PLC system, but as a first approximation in the development of a control system, this type of simulation is suitable (Fig. 2).

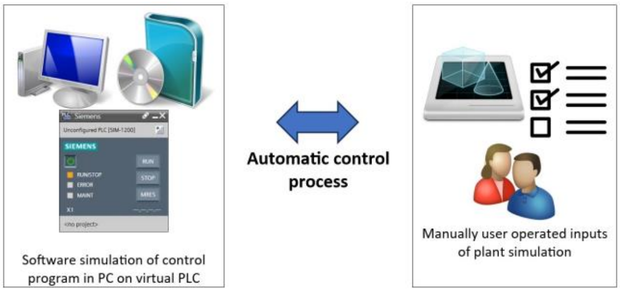


Figure 2. Software to User Simulation - Software simulation on a computer with manual software inputs

2.2 Software to User with Partial Visual Automated Simulation - Software simulation with manual inputs and partially visualized automatic processes

Simulation of a PLC system started on a computer on a virtual PLC with automatically started visualizations of the processes of the controlled system (dynamic visualizations of objects are used in the form of dynamic display according to the state of the system or animation of movements (shift, rotation) to indicate the function of the system (Fig. 3).

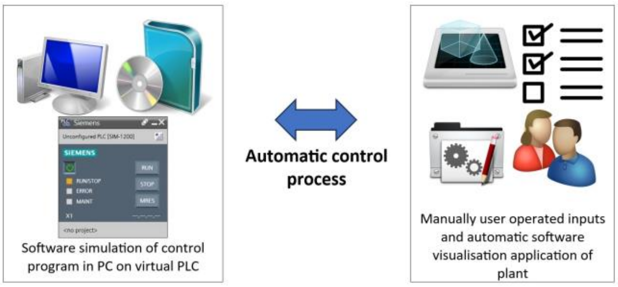


Figure 3. Software to User with Partial Visual Automated Simulation - Software simulation with manual inputs and partially visualized automatic processes

The individual values of the input variables must still be entered by the user using input entities (simulation tables or individual types of input fields) and to a large extent the user still replaces the controlled system. Some functions in the program are supplemented so that they at least partially replace the real controlled object and other connected real devices. This method of simulation testing is closer to the real process in a controlled system. However, the creation of this type of simulation requires additional activities for the creation of additional programs for visualization and imitation of real processes in a controlled system, which, however, are not yet a complete model of the controlled system. The disadvantage is that it is a virtual process, which neglecting some facts can significantly differ from actual real processes. This procedure is suitable for testing the initial system management concept. In addition, this type of simulation already enables the presentation to customers who do not have experience in creating a program for PLC (Fig. 3).

2.3 Full Software to Software simulation - Software simulation controls the complete software model of the controlled system

Simulation of a PLC system in a loop with a controlled system model. The controlled system model is run as a simulation in another simulated virtual PLC or in the same simulated control virtual PLC (as far as the complexity of the model and the computing power of the simulation software allow) (Fig. 4). The simulated control program thus controls a completely simulated controlled system running in automatic simulated mode. The controlled system is created as a precise mathematical model of the real system, which is run in a virtual simulated PLC. This method of simulation is more demanding, as it is also necessary to simulate the controlled system, which can be a rather demanding process in some cases. This method of software simulation is also more demanding on hardware (Fig. 4).

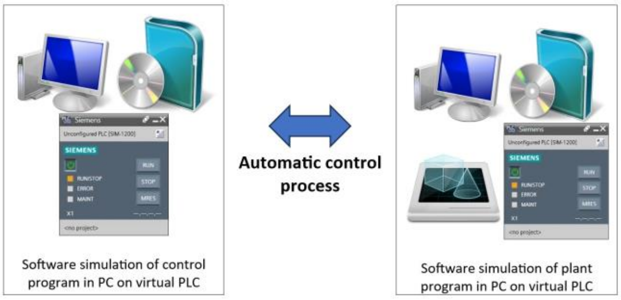


Figure 4. Full Software to Software simulation - Software simulation controls the complete software model of the controlled system

2.4 Hardware to User Activated Sensors model - Hardware PLC controls replacement hardware manually imitating the controlled system

Hardware simulation of the control system on a real PLC training stand, where the program is run in a real PLC and the controlled system is replaced by real sensors and actuators that are connected to the PLC training stand (Fig. 5). However, the sensors and actuators are not part of the controlled system, but are outside it at the PLC training stand. The sensors are activated by the user in an alternative way. The simulation is already in the hardware controls the hardware mode, so it is possible to detect errors and deficiencies that could not be detected by software simulation. However, the controlled hardware does not respond automatically according to the actual controlled device, but is activated by the operator (Fig. 5).

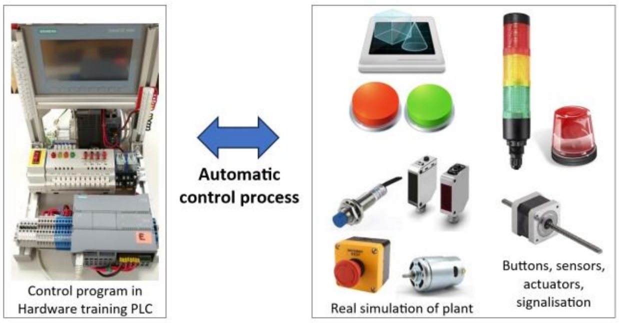


Figure 5. Hardware to User Activated Sensors model - Hardware PLC controls replacement hardware manually imitating the controlled system

2.5 *Hardware in-the-loop Simulation - Hardware PLC controls hardware PLC with an automatically running simulated model imitating the controlled system*

Hardware simulation on a PLC training stand that controls the controlled system replaced by another PLC training stand in which the model of the controlled system is running (Fig. 6). Controlling and controlled PLCs are connected together by respective inputs and outputs. The simulation is in mode where hardware controlling other hardware. Controlled PLC is an almost identical replacement of the real system and its behaviour is automatic and almost identical to the real model (Fig. 6).

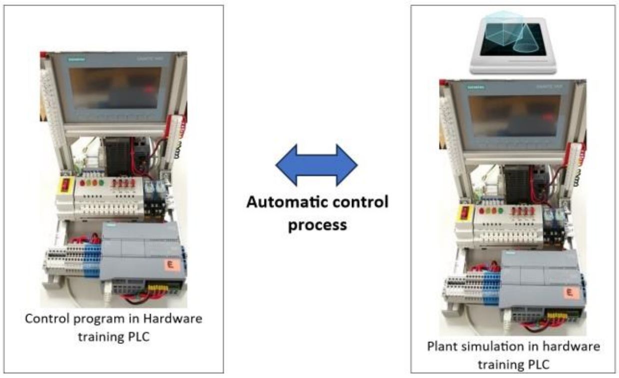


Figure 6. Hardware in-the-loop Simulation - Hardware PLC controls hardware PLC with an automatically running simulated model imitating the controlled system

2.6 *Real control PLC with Real plant application in parallel with plant simulation*

Application on a hardware PLC installed in the target application, which controls the application - a real controlled system (plant) (Fig. 7). This is the final stage of the development of the control system, where only the final experiments and calibration of sensors and actuators with a real PLC are carried out. A simulation model of the real application can be run concurrently with the real application as a digital twin of the real application. The results of the simulation model and the real application are compared, and from this it is possible to predict the behaviour of the real application, and it is also possible to carry out diagnostics in the event of a failure of the real application for quick elimination of the failure. The simulation model can be connected to signals from sensors and actuators and its behaviour should thus copy the real application (Fig. 7).

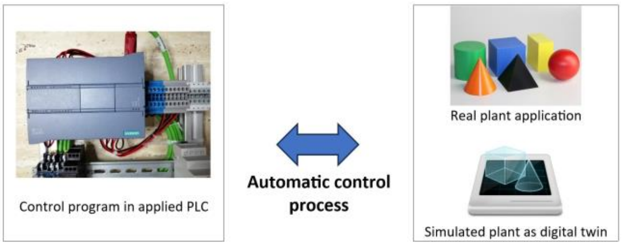


Figure 7. Real control PLC with Real plant application in parallel with plant simulation

3 DESIGN OF VARIABLE REDUNDANT STATION FOR LIQUID SUPPLY - HARDWARE AUTOMATIC SIMULATED PROCESS

The design (Fig. 8) shows the design of the station for the production and supply of chemical substances. The system mainly contains mixing tanks T4 and T5, which are intended for mixing and production of a chemical substance consisting of two components in tanks T1, T2 or T2 and T3. In operation, there is a problem when it is necessary to maintain the continuous preparation of the chemical, but the reactor tank T4 often gets into a state of failure due to the chemical reaction. Another identical T5 reactor tank was added to the system. The system is prepared in such a way that it is possible to automatically prepare the chemical substance in the spare tank and for now it is possible to carry out maintenance and repair of the first reactor vessel. The T1 and T3 tanks have the same chemical for ease of installation.

The figure 8 shows the design of a model workplace for the development of a control workplace, and for simplicity, the supply of tanks T1, T2, T3 is shown by a single tank T6, from which the chemical components are pumped by pumps P1, P2 and P3. The production process can be varied, and in order to avoid technology failure, the system is supplemented with other elements and subsystems. This is a test station design for program debugging and testing for a PLC, so the drain and storage tank is replaced by a single T6 tank for simplicity.

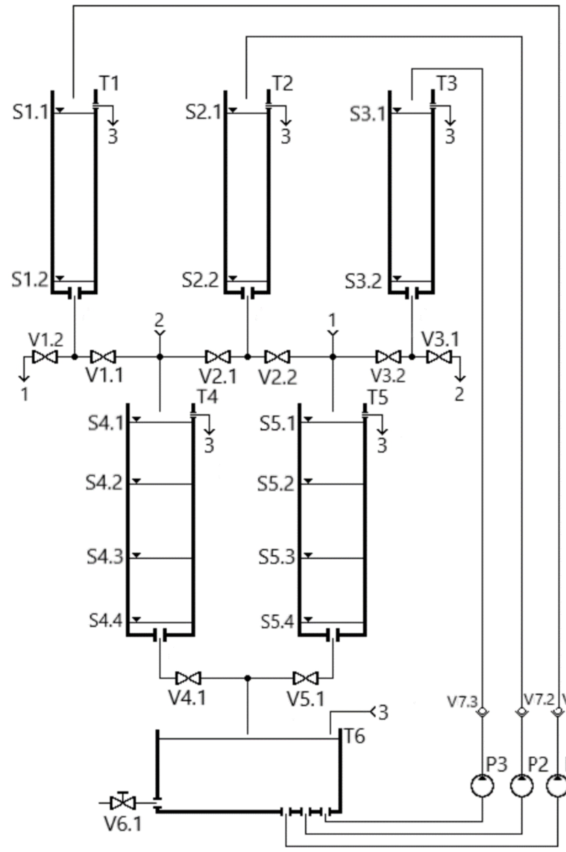


Figure 8. Design of a system of tanks and reactor tanks T4 and T5 for the production of chemicals

The S X.X sensors will be implemented using two-state float sensors that are resistant to aggressive chemical substances. And they will be connected as switching sensors that will generate a logic level of 1 or 0. In the next stage, for the sake of operational safety, submersible water level pressure sensors with an analog output will be added to individual containers. Water levels will be evaluated in two different ways.

The design of the electrical layout is shown in the following figure (Fig. 9) and includes the use of an industrial logic controller PLC S7-1200. The sensors are shown in the diagram as switches in the "Input signals" block. The valves are controlled by an electromagnet - a solenoid, and the diagram provides for the placement of service manual buttons in the event of a malfunction or service of the device so that each valve can be opened manually. Solenoid valves with NC (Normally closed) mode are designed, which are closed when the supply voltage is switched off. The choice of these valves is based on the nature of the production operation. The connection of the pumps is solved with the help of electromagnetic relays, and the connection will be adjusted later with the possibility of turning on the pump manually. At the same time, for back-checking, a signalling LED is also placed in the scheme for the possibility of checking the correct operation of the device.

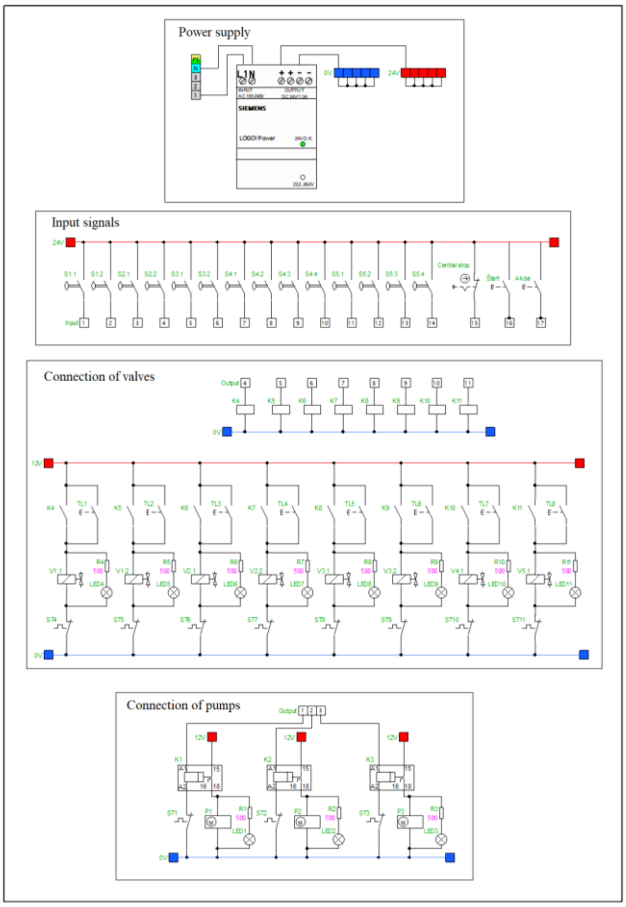


Figure 9. Electrical diagram of the system

3.1 *Design of control algorithm*

The first option is to use it in a simple mode, as it was before the treatment, in such a way that only tanks T1, T2 and T4 are used, and the chemical preparation process will take place only in this part. Changes in the levels in the tanks will be detected using float sensors and signals will be sent to the PLC inputs. After reaching the full state in the reactor tank, it will then be possible to release the prepared chemical into the next process.

The second possibility is the parallel use of additional containers, so that the process is duplicated for the alternative implementation of the entire process or to support the production of a higher volume of chemicals.

Another option is the creation of a three-component chemical mixture, which is created in a ratio defined by the position of the liquid height sensors. An example of the system function algorithm design is shown in the following figure (Fig. 10).

The mixing ratios of the three-component chemical substance are defined by the position of the liquid height sensors, but it is also possible to create other proportions of the mixture by using other planned continuous liquid height sensors with analog output, and the user can set the ratio of the components himself.

After defining the variables (Fig. 11) in the control system project, the system is further solved. For the simplicity of the simulation, the sensors are currently replaced by memory variables in the design so that simulations can be easily solved in the design process.

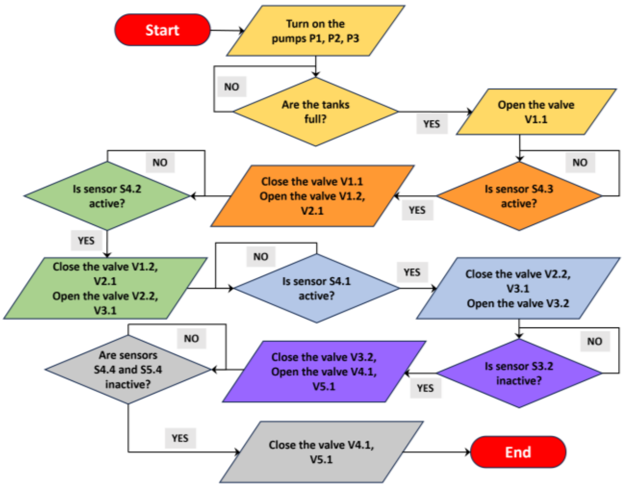
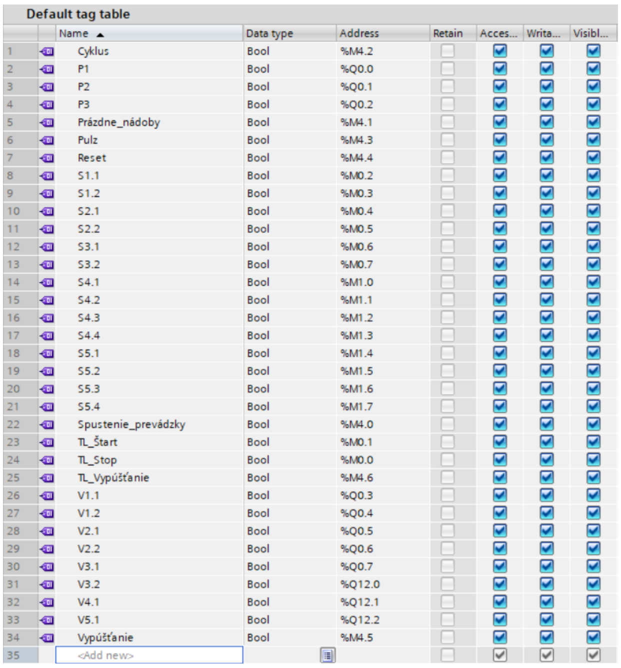


Figure 10. Control algorithm



Default tag table

	Name ▲	Data type	Address	Retain	Acces...	Writa...	Visibl...
1	Cyklus	Bool	%M4.2	☐	☑	☑	☑
2	P1	Bool	%Q0.0	☐	☑	☑	☑
3	P2	Bool	%Q0.1	☐	☑	☑	☑
4	P3	Bool	%Q0.2	☐	☑	☑	☑
5	Prázdne_nádoby	Bool	%M4.1	☐	☑	☑	☑
6	Pulz	Bool	%M4.3	☐	☑	☑	☑
7	Reset	Bool	%M4.4	☐	☑	☑	☑
8	S1.1	Bool	%M0.2	☐	☑	☑	☑
9	S1.2	Bool	%M0.3	☐	☑	☑	☑
10	S2.1	Bool	%M0.4	☐	☑	☑	☑
11	S2.2	Bool	%M0.5	☐	☑	☑	☑
12	S3.1	Bool	%M0.6	☐	☑	☑	☑
13	S3.2	Bool	%M0.7	☐	☑	☑	☑
14	S4.1	Bool	%M1.0	☐	☑	☑	☑
15	S4.2	Bool	%M1.1	☐	☑	☑	☑
16	S4.3	Bool	%M1.2	☐	☑	☑	☑
17	S4.4	Bool	%M1.3	☐	☑	☑	☑
18	S5.1	Bool	%M1.4	☐	☑	☑	☑
19	S5.2	Bool	%M1.5	☐	☑	☑	☑
20	S5.3	Bool	%M1.6	☐	☑	☑	☑
21	S5.4	Bool	%M1.7	☐	☑	☑	☑
22	Spustenie_prevádzky	Bool	%M4.0	☐	☑	☑	☑
23	TL_Štart	Bool	%M0.1	☐	☑	☑	☑
24	TL_Stop	Bool	%M0.0	☐	☑	☑	☑
25	TL_Vypúšťanie	Bool	%M4.6	☐	☑	☑	☑
26	V1.1	Bool	%Q0.3	☐	☑	☑	☑
27	V1.2	Bool	%Q0.4	☐	☑	☑	☑
28	V2.1	Bool	%Q0.5	☐	☑	☑	☑
29	V2.2	Bool	%Q0.6	☐	☑	☑	☑
30	V3.1	Bool	%Q0.7	☐	☑	☑	☑
31	V3.2	Bool	%Q12.0	☐	☑	☑	☑
32	V4.1	Bool	%Q12.1	☐	☑	☑	☑
33	V5.1	Bool	%Q12.2	☐	☑	☑	☑
34	Vypúšťanie	Bool	%M4.5	☐	☑	☑	☑
35	<Add new>			☐	☑	☑	☑

Figure 11. Defined PLC variables - PLC Tags

3.2 *Design of control networks*

Function block FB3 with the username task2 contains the definition of the operation of the device (Fig. 12). Another functional block FB2 will deal with the simulation of the operation of the liquid height sensors. These function blocks will be executed in parallel.

Function block FB3 task2 will contain networks for creating this task. Network 1 (Fig. 13) implements the start of the work cycle of the device and enables the emergency shutdown of the entire device. SR flip-flop circuit is used for control. In this network, an emergency discharge of liquid is also possible.

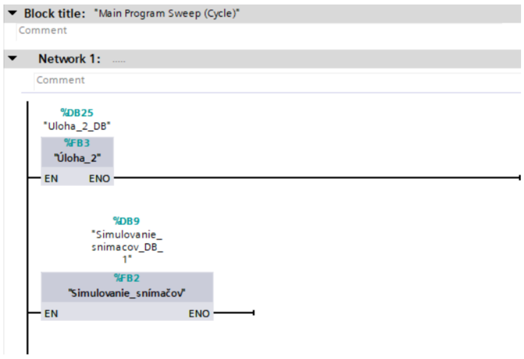


Figure 12. Design of the main block of the program

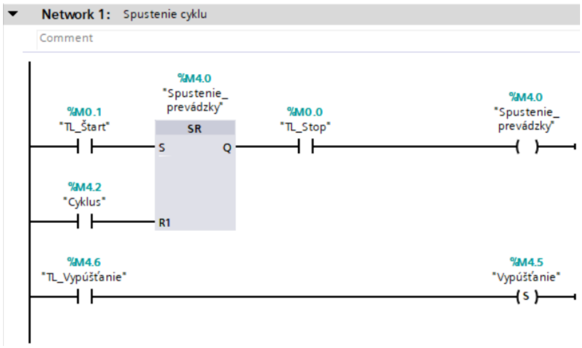


Figure 13. Network 1 – starting the work cycle of the device

In the next network 2 (Fig. 14), the status of individual tanks T1, T2 and T3 is detected. If all the sensors are in the state of signalling the absence of liquid, then the variable M4.1 empty container is changed and the reset of the duty cycle is also activated and the draining of the tank is stopped.

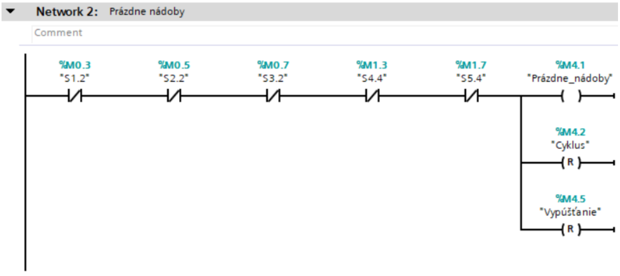


Figure 14. Network 2 – detecting the status of tanks

In network 3 (Fig. 15), when the system is started (starting operation) and the state of empty tanks T1, T2 and T3 is detected, individual pumps are switched on to transfer liquid from the reservoir to tanks T1, T2, T3.

The pumps are then deactivated by liquid height sensors at the level of maximum filling of individual tanks. The timer that is used in the network is related to the technical implementation to prevent the system from oscillating and undesired turning off of the pumps.

In network 4 (Fig. 16), gradual filling is realized from each tank T1, T2 and T3 according to the activation of individual liquid height sensors. And analogously, network 5 (Fig. 17) realizes the filling of the reactor vessel T5.

In network 6 (Fig. 18), the finished chemical is discharged into the technological process from containers T4 and T5 into container T6, and this process will last until the moment when the state of complete emptying of tanks T4 and T5 is detected using sensors S4.4 and S5.4. At this moment, the work cycle will be finished and the Cycle variable reset and discharge will be activated, and the whole work cycle can be repeated again.

Network 7 (Fig. 19) enables the counting of the implemented working cycles of the device.

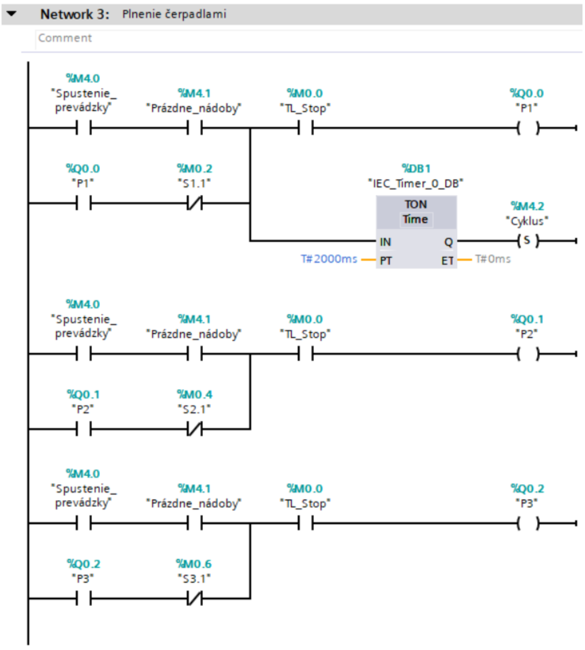


Figure 15. Network 3 – Filling the tank with pumps

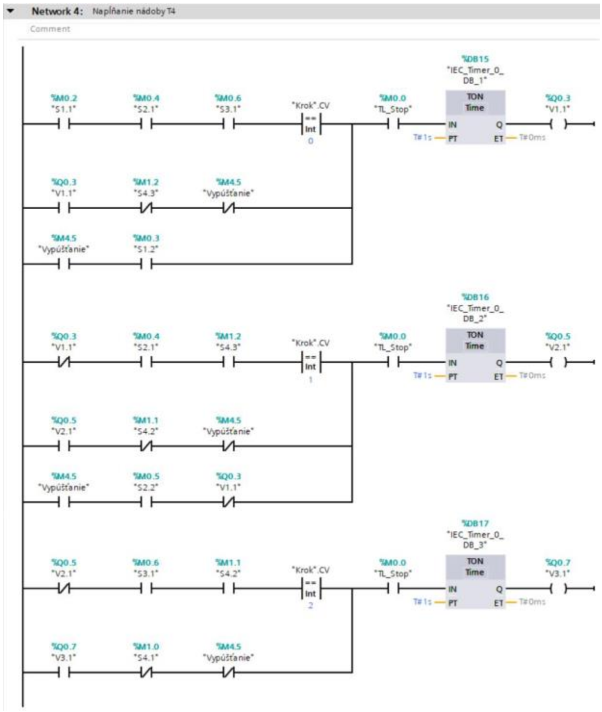


Figure 16. Network 4 – Filling the reactor vessel T4 with individual components of the chemical

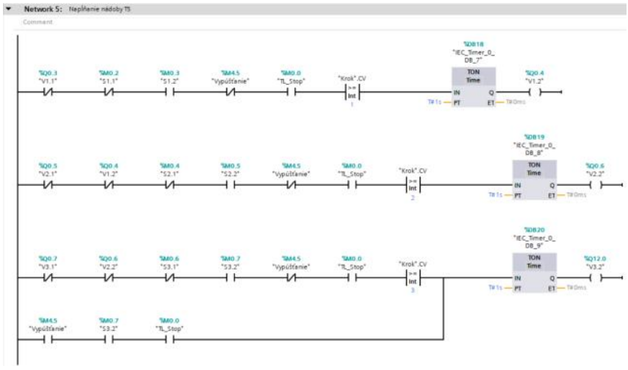


Figure 17. Network 5 – Filling the T5 reactor vessel with individual components of the chemical

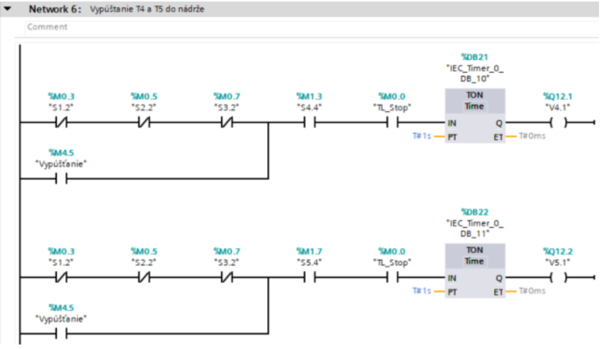


Figure 18. Network 6 – emptying reactor vessels

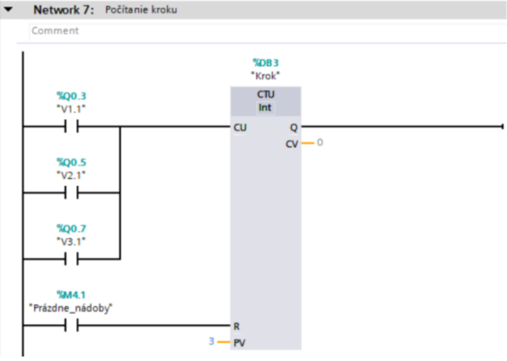


Figure 19. Network 7 – counting the implemented working cycles of the device

4 SIMULATION OF THE OPERATION OF A STATION FOR THE PRODUCTION OF CHEMICALS

For testing the program for the production of chemicals, another functional block will be created - Simulating sensors, which will imitate the real system, and thus it will be possible to test the functional block for the production of chemicals first on this hardware model. In this way, the real operation will be completely replaced and it will be possible to test the functionality of the designed program first in the form of a simulation.

For this purpose, a functional block was designed where the filling of individual containers and the functionality of individual liquid height sensors in individual containers will be simulated.

Network 1 (Fig. 20) in the function block Simulation of sensors will need to create a periodic pulse generator (0/1) in order to simulate the gradual filling of containers. For this generator, the "Timer TP" block is used, which is cyclically started and turned off with a period of 50ms. We will be able to change this time depending on how quickly the simulated container will be filled.

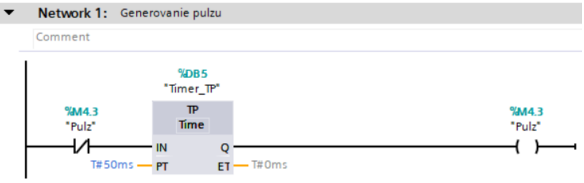


Figure 20. Network 1 (Sensor simulation) - generator of periodic pulses

The operation of the pulse generator in network 1 is shown in the following figure (Fig. 21).

Network 2 (Fig. 22) solves the simulation of filling the tank T1. The filling of container T1 is carried out using the CTUD block, which adds an integer value every time after the leading edge is introduced and after the set time of the generated pulse Pulse has elapsed. The CV (current value) is the current number of pulses, while one pulse will mean an increase in the liquid level by one unit. A constant of 250 is set in the value PV (preset value), which if our reader CTUD reaches in the value CV, then the output of the reader QU will be activated to the value of logic 1, which will be stored in the state variable of the sensor S1.1, and the container T1 is thus in the state - filled. After opening one of the valves V1.1 or V1.2 to drain the tank T1, the gradual draining of the tank T1 is activated again by generating pulses and gradually subtracting these pulses, since these pulses are already fed to the CD input, which reduces the CV value every time after each rising edge of the pulse. This countdown thus simulates the emptying of container T1 until the moment when the value of CV reaches the value "0", that means that container T1 is empty. The value of the quantity QD reaches the value of logical 1 if the state of the counter in the variable CV is equal to 0 and this value is in this network as a negated value (using the NC block) brought to the variable of the sensor S1.2 (M0.3) which signals the emptying of the container T1. With variable M4.4, it is possible to reset the operation of the counter at the R input. This network therefore completely replaces the real object of the container T1 (Fig. 22).

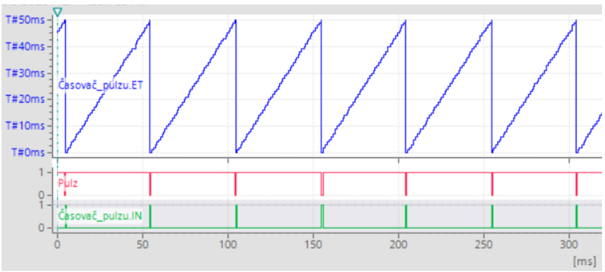


Figure 21. Functional course of generated pulses in network 1

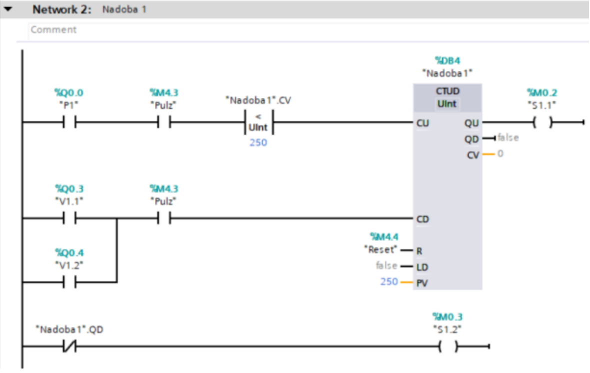


Figure 22. Network 2 (Simulation of sensors) – filling of container T1

Containers T2 and T3 are realized analogously by the same principle but with their own variables and thus function independently of each other.

Network 5 (Fig. 23) for simulating the operation of the T4 reactor tank works analogously to the T1 vessel. The CTUD block is used again, which has a pulse generator connected to the CU (count up) input, which is active only if at least one of the valves V1.1, V1.2 or V3.1 is active. The CV value will thus increase only until the CV is less than 500 (500ml). The valve V4.1 will activate the emptying of the container at the CD input (Count down) again using the pulse generator until the CV value reaches 0 and the container is therefore completely emptied and the sensor S4.4 is set to logic 1 by negating the QD value and will signal emptying the tank T4. Other sensors will be gradually activated or deactivated according to the CV value using the conditions where the tank was divided into thirds, at each third of the tank level, another sensor is activated/deactivated. This network completely replaces the real model of the T4 reactor tank. The T5 reactor tank is simulated analogously but with different variables, sensors and valves.

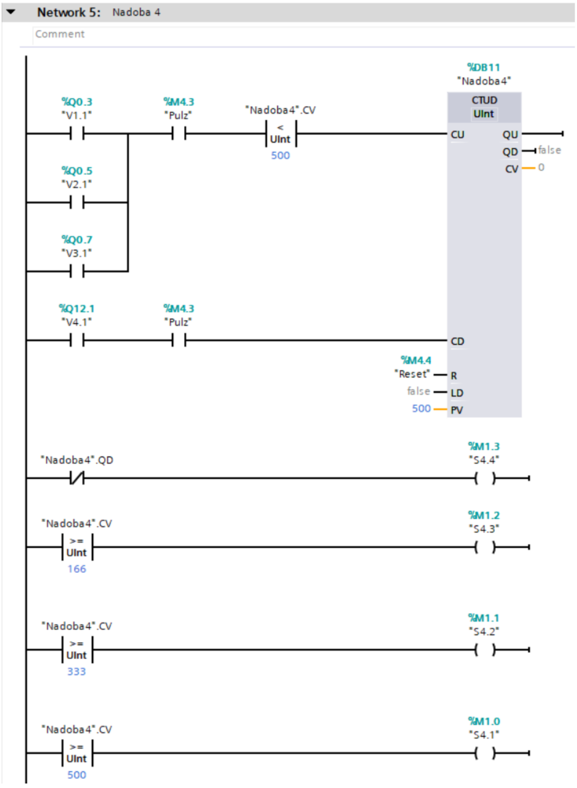


Figure 23. Network 5 (Sensor simulation) – simulation of the T4 reactor tank

5 SIMULATION HMI INTERFACE

To simulate the functionality of the system, an environment is created in the HMI (human machine interface) interface for a better visualization of the processes in this system. The HMI interface is a graphical arrangement of visual objects for entering operator inputs and visual objects for displaying the status of individual subsystems. Buttons, switches, input-output windows, animated graphic objects, slide bars and other objects are used. The functionality of the HMI interface is tied to the control program for the PLC controller and the simulation program for the plant. The HMI interface must be designed in such a way that it enables the operator to operate the technical equipment, even without knowledge of programming and creating a control system. The following figure (Fig. 24) shows the state of empty tanks when the system is turned off.

After switching on, the process of filling containers T1, T2 and T3 starts automatically (next picture). The flow of liquids is shown graphically and by changing the color of pipes and pumps (Fig. 25).

After the containers T1, T2 and T3 have been filled, the process of automatically filling the reactor tanks T4 and T5 will begin, by gradually emptying the containers T1, T2 and T3. In figure 26 valve V1.1 is activated and tank T4 is being filled. Sensor S1.1 already signals that container T1 is no longer full and is starting to be emptied. Sensor S4.4 signals that reactor tank T4 is no longer completely empty.

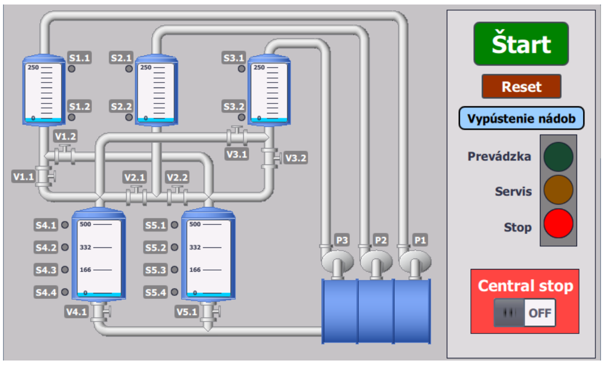


Figure 24. Simulation - system off

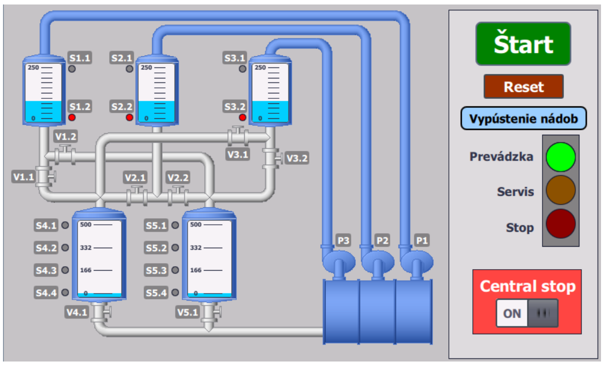


Figure 25. Simulation – filling of containers T1, T2 and T3

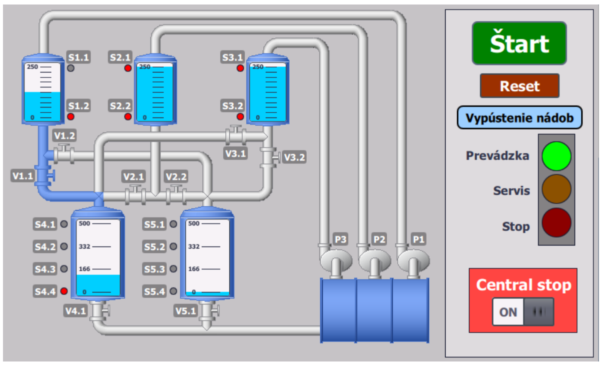


Figure 26. Filling the reactor tank T4 using valve V1.1

The simulation continues (Fig. 27) by reaching the level of sensor S4.3 in tank T4, valve V1.1 was automatically deactivated and valve V1.2 was activated, and reactor tank T5 began to be filled with liquid from vessel T1. At the same time, the valve V2.1 was activated and thus the filling of the tank T4 with the liquid from the tank T2 began. This state will last until the moment when the level in the tank reaches the level of sensor S4.2. Analogously, container T3 is also emptied into both reactor tanks.

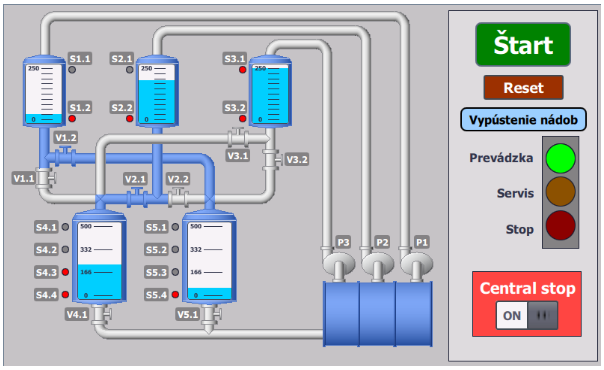


Figure 27. Filling of reactor tank T4 using valve V2.1 and tank T5 using valve V1.2

This is followed by the discharge of the reactor tanks with the finished chemical using valves V4.1 and V5.1 (Fig. 28).

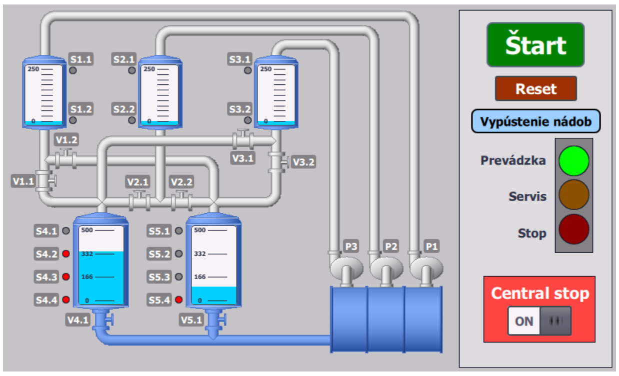


Figure 28. Draining of reactor tanks T4 and T5

The application still contains a reset button, the operation of the entire system is restored. The central stop allows the entire application to be stopped at any moment by immediately stopping the pumps and blocking all valves. The button to empty the containers allows the containers to be emptied at any time and the cycle ends.

6 CONCLUSIONS

Previous procedures in the design of control systems were usually implemented in such a way that they required the existence of a controlled system and experimenting with a real object thus brought great risks and dangers. Crisis situations could not be tested experimentally with a real controlled system, because in the case of a real object, in case of unsuccessful control, it would mean the collapse of the system. Gradually, with the development of the level and performance of the software, a development level was reached where it is possible to simulate even complicated systems with control, even in real time. This allowed the developers of control systems to test the control system while interacting with the simulation model of the controlled system, and thus, in case of control failure, tragedies and disasters did not happen. In practice, there are many such systems that are very complicated and risky for experimentation. There is therefore a demand for a trained robust control system that is able to handle even crisis situations that should not occur under normal circumstances. However, in reality, the impossible often becomes a reality, and a well-trained control system can save human lives and material values. In addition, the development of such a complicated control system can be done much faster, and the simulations can be solved by several developers on different computing systems at the same time. The control system tested in this way is more durable and stable and also brings higher security of the control process. The created virtual model of the control and controlled system thus creates a digital copy, but often called a digital twin, which can run simultaneously with the real system. The results of both of these systems can be compared to create a powerful diagnostic tool for detecting unwanted states and enabling the prediction of dangerous system states [Holubek 2014, Simonova 2017, Bobovsky 2018, Bulej 2018, Saga 2018 and 2020, Nikitin 2020, Hortobagyi 2021, Kelemen 2021, Kelemenova 2021a,b, Olejarova 2021, Pivarciova 2021, Sincak 2021, Suder 2021, Zelnik 2021, Hroncova 2022a,b, Mikova 2022, Virgala 2022].

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