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Design of an integrated automation and control system using Petri nets: Case study

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Abstract: Integrated automation and control system (IACS) based on the discrete events control using Petri nets (PN) that encompasses the design, analysis, and validation of models of industrial pumping systems are not commonly used. Our case study is the design, simulation, and initial implementation of a supervision system using GHENeSys PN and EROS software at the "San Juan" Pumping Station in Santiago de Cuba, Cuba. These tools allow describing the models of the states of the local automatic process and the operation of the Supervisor to consider the functions of Preventive Maintenance and Alarm Treatment. The IACS starts from the MatLab simulation of main control loops and later uses the GHENeSys extended hierarchical net to model a modularly structured integrated automation system that responds to synchronized functional demands. This methodology has the advantages of full hierarchical modularity from local control to production management, various modular verification and validation tools, and full IEC61131 compatibility. This reduces design errors and implementation time with increased integration efficiency.

Keywords: Automatic control, networked control systems, SCADA systems, software systems, supervisory control

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1. Introduction

With the development and modernization of the industrial sector, Integrated automation and control system (IACS) was introduced to achieve good synchronization between local control and intelligent supervision, increasing complexity and requiring greater integration efficiency. Implementing the IACS incorporates alarms and fault protection, decision-making based on statistical parameters, preventive maintenance, quality and production control, and cyber safety (Aguilar et al., 2013; Jakovljevic et al., 2020; Kanamaru, 2020; Raman & Screenivas, 2021). This efficient synchronization is only possible with integrated design (Benitez-Pina et al., 2017; Silva et al., 2008).

The simulation of the process models, in which continuous and discrete control loops are added to achieve total automation, allows the design of multiple control systems traditionally represented in block diagrams (Miyagui, 1996). Such systems have generally been designed independently for continuous (Ogata, 2010) and discrete systems (Murata, 1989). The control object in continuous loops is modeled by transfer functions (Ogata, 2010) obtained from the differential equations that govern the dynamic behavior of the process, while the control object in discrete loops is modeled by discrete event systems, such as Petri nets (Murata, 1989), which determine the sequence of the dynamic operation of the process (David & Alla, 2010). Discrete Event Control Theory is more recent than Continuous Control Theory, and it exists like 1989 presented by Ramadge and Wonham (1989).

At present, there are two basic theories for the formal modeling of discrete event systems, finite automata (Ramadge & Wonham, 1989) and Petri nets (PN) (Kaid et al., 2020; Murata, 1989; Raman & Screenivas, 2021; Theis et al., 2019). The Discrete Event Control theory on PN models that already encompass hybrid systems (integration of continuous and discrete) has advanced strongly (David & Alla, 2010).

Analyzing automatic control evolution, Åström et al. (1996) said: "*Such combinations of logic and differential systems are called hybrids, and in many cases, their evolution can be modeled as discrete event systems (DES). Study of DES is increasingly common and, while on the periphery today, may in the future assume a more central place in control engineering*" (Åström et al., 1996). This prediction is now very near; hybrid automation control systems are closer to the center of industrial control engineering using hybrid PN modeling (David & Alla, 2010) and programmable logic controllers (PLC) implementation with IEC61131 language. Therefore, automation specialists need to create an integrated modeling methodology for PNs compatible with the IEC61131 standard (Nuñez et al., 2020; Silva et al., 2008).

The classical (Silva et al., 2008) and hybrid (Benitez-Pina et al., 2017) GHENeSys extended hierarchical PN modeling methodology allows high compatibility with application programming in IEC61131 languages due to its particularities and its guarantee of using the most complex (hybrid) modeling only in small parts of the model (Benitez-Pina et al., 2017); that is the reason why it is selected to design and validate the aqueduct system.

In the current work, an IACS based on the control of discrete events (DES) is designed, using the GHENeSys Petri Nets (GPN) (Benitez-Pina et al., 2017) to be applied in the control of the Pumping Station "San Juan" of the aqueduct in Santiago de Cuba, Cuba, Figure 1. Also, a supervisory system is included using the EROS software (Rigó et al., 2018). The advantages of the GHENeSys modeling methodology for the integrated hierarchical modular design and implementation, including its IEC61131 compatibility at all levels, are demonstrated. The novelty of this hybrid design methodology was applied in the water service sector.

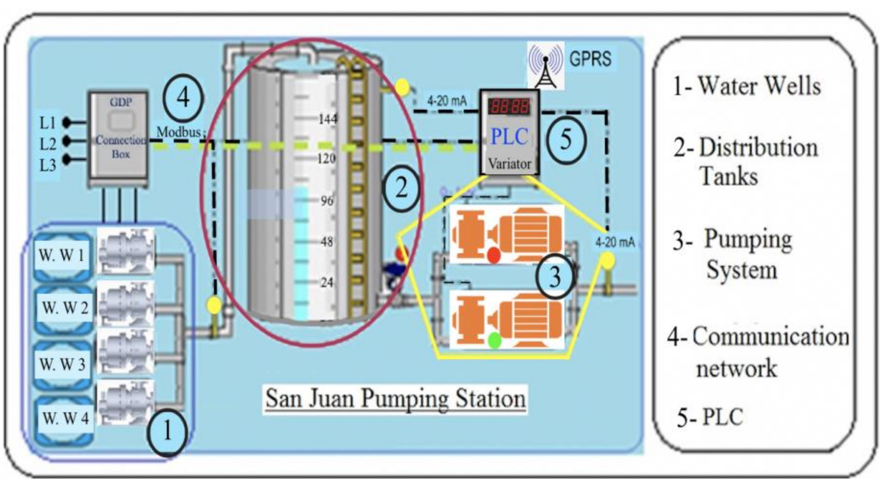

Figure 1. San Juan system (Santiago de Cuba) with its subprocess associated.

The analysis, design, and validation of IACSs using GPN have not been widely used due to their limited international dissemination (Benitez-Pina et al., 2017; Silva et al., 2008). Some research in the related field is considered below.

A Place/Transition Petri nets (P/T PN) allow modeling of multiple production processes and their behavior, such as sequence, concurrency, synchronism, and parallelism (David & Alla, 2010; Murata, 1989). However, several extensions to the P/T PN are proposed to increase the representation capacity of the PN. A list of related works involving PN extensions: Controlled PN (CtlPNs) and Labeled PN (LPN) (Holloway et al., 1997), Signal Interpreted PN (SIPN) (Frey & Litz, 1998), Automation PN (APN) (Uzam et al., 1998), among others, reveal techniques that can ensure the modeling of the global behavior of the system. However, several current studies (Borges & Lima, 2018; Kaid et al., 2020; Luo et al., 2018; Theis et al., 2019) highlight the gap between these PN control design methods and their implementation in the most widely used industrial device, PLCs. In (Silva et al., 2010), it is deepened in which factors have favored this difference and its solution variants (SIPN, APN, and GPN) comparatively.

The use of auxiliary places with extended arcs to condition controllable transitions, the hierarchical use of macro-elements, and the function that assigns control actions give GPN (Silva et al., 2010) the advantages over APN and SIPN, but only at the local automatic level. Hierarchical modular design differentiating between most discrete parts and some small continuous parts (Benitez-Pina et al., 2017) reduces the PN-PLC gap to integrate local automation-level functions. However, the modern integration between local automation and enterprise supervision and management (within IACS) widens the PN-PLC gap because it requires greater synchronization of multiple functions.

The strong presence of the discrete event control theme can be verified in any prestigious database such as WoS and Scopus, where there are 5345 articles from 2016 to the present. For example, the proper use of Petri nets in a distributed control system in which different functions are assigned to local controllers that have physical access to certain sensors and actuators of the system is analyzed (Jakovljevic et al., 2020); where distributed control tasks for local net controllers are automatically designed. In (Basile et al., 2020), PN models are used to identify unobservable sequences that determine conditions of importance for the system, allowing critical situations to be predicted and achieve optimization. In (Lutz-Ley & Lopez-Mellado, 2018), a novel method is proposed to define the stability of safety PN models. A PN-based mathematical analysis for the fault tolerance of a software-defined net is presented (Aly & Kotb, 2018). All these examples confirm the importance and current interest of PN models for designing automation systems at the local and supervisory levels. Still, they present integrative solutions, neither in control type nor hierarchical levels.

The development of methods to verify and validate PN models of automated systems is also maintained. In (Kaid et al., 2020), colored PN is used to design and implement the reconfigurable manufacturing system. In (Luo et al., 2018), an approach in ordinary Petri nets is used to analyze, simulate, and verify programs in ladder diagram (LD), managing to detect unwanted sequences and finding the correct sequence using reachability graphs (RG). In (Yue et al., 2019), an analysis method is proposed using basic marking in compacted reachability graph (BRG), which allows solving the problem of estimation of low-cost transition sequences using LPN with unobservable transitions. These examples show that the design, verification, and validation in PN are not fully resolved because it is a current topic with complex methods (colored PN, RG, BRG), and they do not have full IEC61131 compatibility with integrality between hierarchical levels.

PN models are widely used in the planning and control of industrial processes. For example, in (Lin et al., 2016), a timed PN is developed to describe the operation according to recipes of a chemical batch process (Batch) to achieve optimal planning and control of the process using an optimization strategy computing a valve control matrix (VCM) until obtaining efficient control commands. In (Li et al., 2019), a modified dynamic programming method (MDP) applied to models in PN is used to solve a planning problem to minimize total energy consumption in flexible manufacturing systems (FMSs). From this, we concluded that the PN design of integrated automation with planning is a high research subject. Still, there are complex methods (VCM in timed PN, MDP in PN) and do not have full IEC61131 hierarchical compatibility.

This analysis shows that PN design, verification, and validation methods of local and distributed automation systems are current researcher themes but not fully resolved. Several Ibero-American universities and companies collaborate on the hybrid hierarchical GHENeSys PN methodology with high-level modularity to develop applications using the IEC61131 (Acosta, 2015; Benitez-Pina et al., 2017; León & Alvarez, 2019; Reynard et al., 2008; Silva et al., 2008; Nuñez et al., 2019).

3. Result and discussion

The GHENeSys integrated automation design methodology (Benitez-Pina et al., 2017; Silva et al., 2008) uses several steps or stages that help in its execution to achieve a complete integrated design that allows efficient programming of the IACS. The steps for the IACS of the San Juan wells of the Santiago de Cuba aqueduct are explained below, demonstrating its advantages over other existing methodologies (briefly listed in section 4).

Initial steps in GHENeSys methodology develop a characterization of the San Juan Pumping Station to define IACS subsystems. It includes three main control loops simulated in MatLab to study the best algorithms to use: On/Off control with hysteresis at the tank level, PID algorithms in the pressure control, and speed control with a frequency inverter in the pumps determined.

In Figure 2, a pressure control loop behavior is shown using MatLab software with the corresponding numerical values and the simulation graph of the loop against disturbances (Acosta, 2015). The PID adjustment values obtained were Kc = 0.06, Ti = 0.6, and Td = 0.008 using MatLab tools. The proposed control algorithm is simulated by disturbing it with variations in water consumption pressure (Ps). It is verified that peaks are attenuated by more than 80% in the controlled flow (Qs). Still, it is impossible to simulate its behavior integrated into the rest of the automation. This loop must be integrated into the entire automation sequence (start-stop, operating modes, attention to limits and faults, automatic protection, preventive maintenance, and others). Then the operation sequence of the entire process, where these control loops are inserted, is studied inside general requirements to create effective integration.

In the GHENeSys methodology, the functional requirements were conceived as the needs of the subsystems that must be satisfied in the implementation. Five subsystems were grouped: Wells, Tank, Pumping System, Communications, and Supervisory System; each with its characteristics and requirements, studied for coordinated and continuous work. For example, among other conditions, filling the Tank using the Well pumps is performed only at the beginning of the process. On the other hand, the Tank level control method will be on/off with hysteresis and will depend on the operator's level reference and adjustable hysteresis. The pumping system considers, among other requirements, that it must drive the water at a certain speed depending on consumption and that the system must stop automatically if there is a failure in the variable speed drive, the PLC, or any pumping equipment. Regarding the communication network, it must be properly monitored by the SCADA and be able to transmit the data of the electrical parameters of the pumping station to the PLC. Lastly, the supervisory system is aware of international standards, guarantees efficient operation in manual and automatic work modes, and facilitates failure attention and maintenance; further details appear (Acosta, 2015).

It was necessary to define a modular structure of the IACS, as shown in Figure 3, to carry out the formal design of each subsystem model and their associated functions, where different colors indicate vertical relationships in addition to horizontal ones, according to functional requirements of the process.

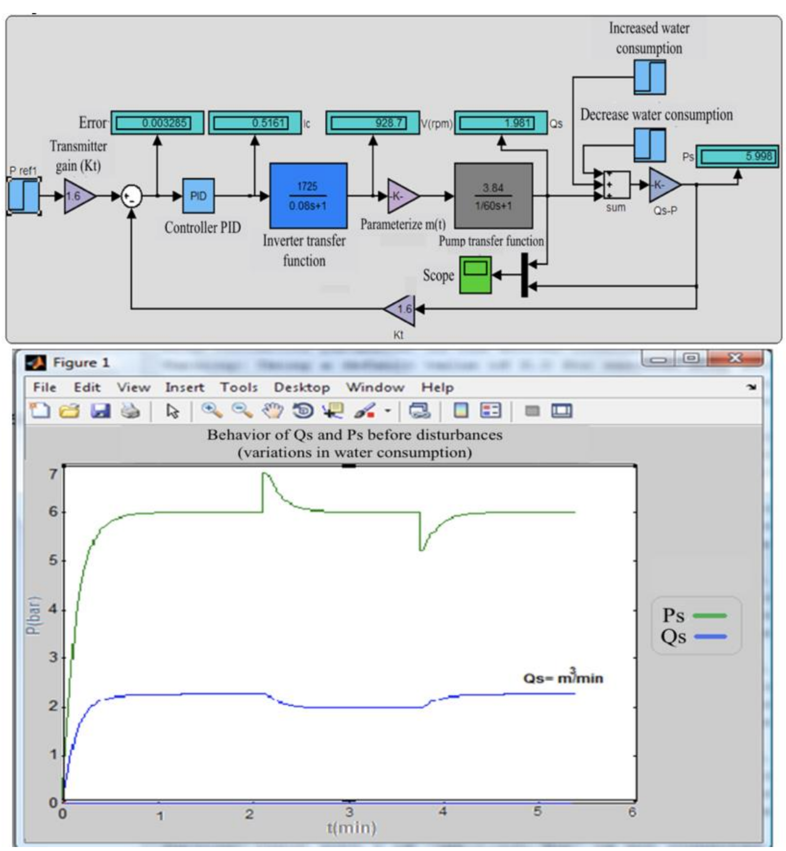

Figure 2. Results of the simulation of the pressure control loop and behavior of Qs and Ps in the presence of disturbances.

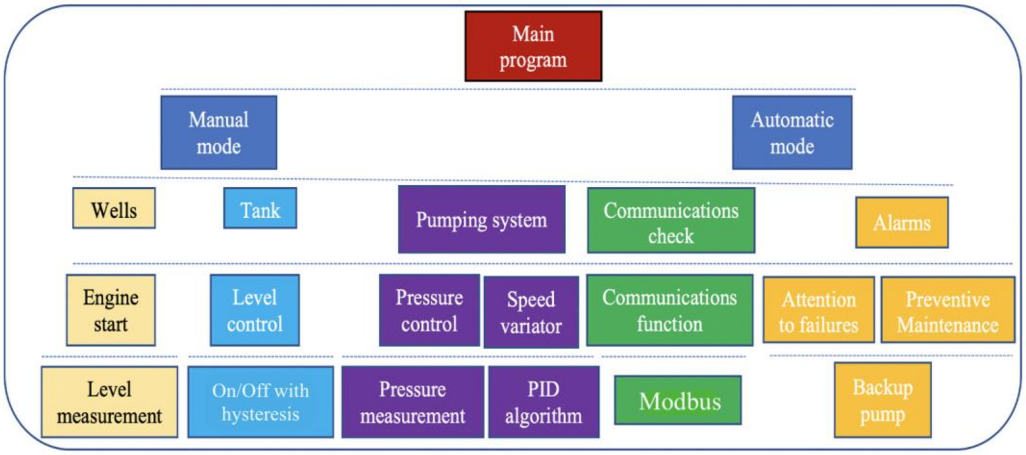

Figure 3. Modular Structure of the IAS.

This modular structure ensures a modular design translatable to IEC61131 that solves different requirements by programming methods, algorithms, and equations, depending on the subroutine that contains them, allowing the reuse of functional blocks and modular programming. Each module is modeled in GHENeSys PN for its design, its properties are verified, and its functional requirements are validated, allowing the design to be refined and translated into compatible IEC61131 programs. Other methodologies (Basile et al., 2020; Frey & Litz, 1998; Holloway et al., 1997; Luo et al., 2018; Uzam et al., 1998) do not allow this high modularity to be fully compatible with IEC61131 (Benitez-Pina et al., 2017; Silva et al., 2008).

Each subsystem of the modular design, Figure 3, generates a model in GHENeSys PN. The upper level generates a model that allows the starting and selection of operating modes in three macro-places that, when enabled, activate the models of the second level in manual or automatic, but with priority to emergency mode in dangerous situations. In Manual mode, only the actuators of all the lower subsystems are activated or deactivated for maintenance and repair, but all design requirements are guaranteed automatically. In automatic mode, Figure 4, the sequence is established using macro-places that are controlled by enabling and inhibiting arcs from multiple conditions, thus guaranteeing the integration of sequential and continuous controls. Both are the advantages of GHENeSys over other methodologies that favor modularity, integration, and IEC61131 compatibility. Details of continuous-discrete integration in (Benitez-Pina et al., 2017).

The most important local automatic models were (Acosta, 2015):

a) Turning the pumps on and off (direct start of motors). The first column of blocks is in Figure 3.
b) Level control (on/off method with hysteresis). The second column of blocks is in Figure 3.
c) Pressure control (PID algorithm). The third column of blocks is in Figure 3.
d) Centrifugal pump control (function for speed variation). The fourth column is in Figure 3.

Model a) is used for the control of the well pumps, contemplating the immediate start of the motors with their multiple conditions, such as normal situations, failures, safety, maintenance, and activation of the reserve pump, allowing to show the three possible states: Off (Off), Running (On), and failure. Verification and validation of the GHENeSys model allow improving its integrated behavior from design (Acosta, 2015).

Model b) corresponds to level control. In the model in Figure. 5, the level control of the macro-place P28 represented in Figure 4 is detailed. The left part of Figure 5. includes the conditions for checking the faults and alarms before the simplified automatic sequence by enclosing the basic actions in three macro-places. In the center of the figure are the details of the algorithm using macro-elements to enclose analog actions such as value loads (macro-places P7, P9, and P13) and execution of continuous operations (macro-transitions T5 and T6). This allows for maintaining the IEC61131 compatibility of the hybrid model that no other methodologies have compared to (Benitez-Pina et al., 2017). To the right of Figure 5 is the interrelation with the process.

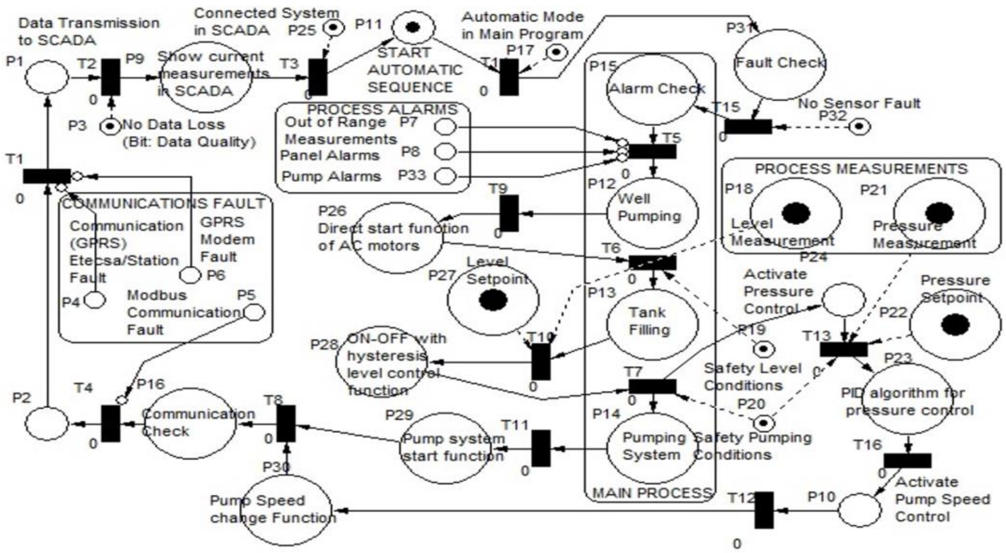

Figure 4. PN Model of the System in Automatic Mode.

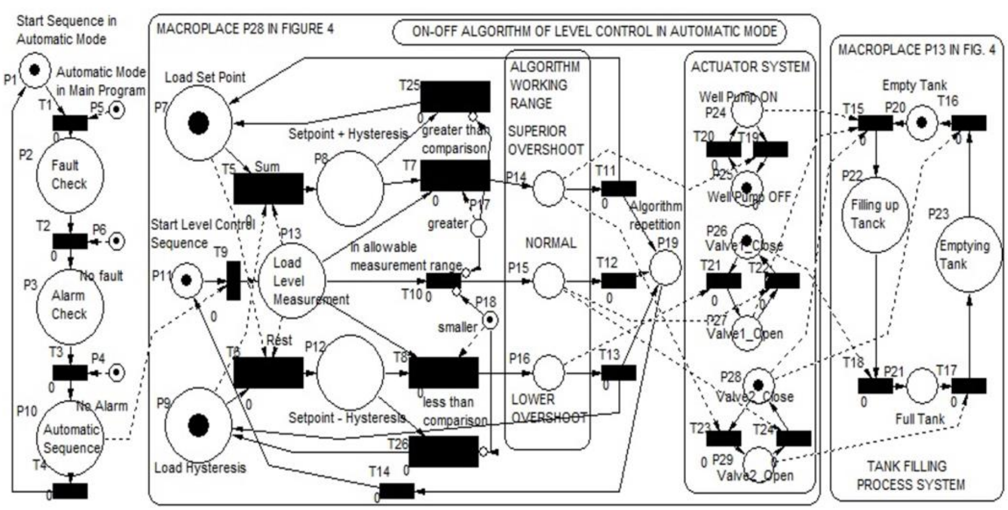

Figure 5. Model of the level control on / off function with hysteresis.

Model c) simulates the pressure control method implemented in the PLC (P23 in Figure 4). In this GHENeSys model (Figure 6) is possible to integrate the continuous control PID algorithm (second block in Figure 6) with the sequential functions of failsafe and predictive maintenance (central and lower part of Figure 6). The use of macro-elements to encapsulate continuous actions and their conditioning through auxiliary places with enabling and inhibiting arcs allows discrete verification and validation to achieve efficient integration, which is not known in other Petri net methodologies.

Model d) describes the internal details of the speed variation function (P30 in Figure 4) and is composed of several internal subnets that simulate the electrical needs to control the pump using a variable speed drive. In the same way as other models, macro-elements and auxiliary places are used to guarantee an efficient continuous-discrete integration and its IEC61131 compatibility from design until the program.

At the upper level, the operation of the supervisory system has the following models (Acosta, 2015):

a) Operation of the SCADA. (Access control and navigation between SCADA screens).

b) Process states are displayed on the main screen. (Normal and abnormal operations of the process).

c) Communications check. (Failure detection and communication guarantee).

d) Alarm check table. (Treatment of current and historical alarms and relevant events).

e) Trends and assortments in decision-making based on historical data. (Decision support system).

f) Operation reports and statistical analyzer results. (Maintenance and enterprise management).

In model A of general SCADA operation, it was necessary to make a table with the screens' distribution and the associated characteristics (Acosta, 2015). This table is used to create all SCADA models. The GHENeSys model of this subsystem presents sequences of access control, activation of operating conditions, and opening of the general synoptic or mimic with access to the auxiliary windows of the SCADA (alarms, trend, reports, and statistical analyzer). Each stage is represented with macro-places and their conditions with auxiliary places and extended arcs that allow simulating its execution in any normal or dangerous situation, which is not allowed to be studied integrally in other discrete methodologies (Aly & Kotb, 2018; Borges & Lima, 2018; Lin et al., 2016; Lutz-Ley & Lopez-Mellado, 2018; Yue et al., 2019;). These macro-places encapsulate the execution details of each one, as in the case of the synoptic or general mimic which these internal details are enlarged in the low hierarchical model (Figure 7).

Model B defines the operation sequence in the SCADA Mimic (Figure 7) and considers the initial condition that allows simulation of the initial state to the operation of the mimic (part 1 in Figure 7) and the state of communications to know if the data have shown are current or previous measurements (part 2). It also indicates the status of the tank level (part 3), the pressure in the supply line (part 4), the flow (part 5), the status of the Working and Reserve Pumps (part 6), and the possible alarms that could occur at any given time (part 7). Flow and pressure SCADA representation is like level, and for that reason was simplified. This model demonstrates that the proposed methodology allows modeling discrete actions, such as the movement between windows (Part 1) with the presentation of current or previous values of the four main continuous variables of the process (parts 3 to 6), all efficiently integrated within the operation of the main SCADA window. This allows us to verify and validate the integration with the simple discrete method.

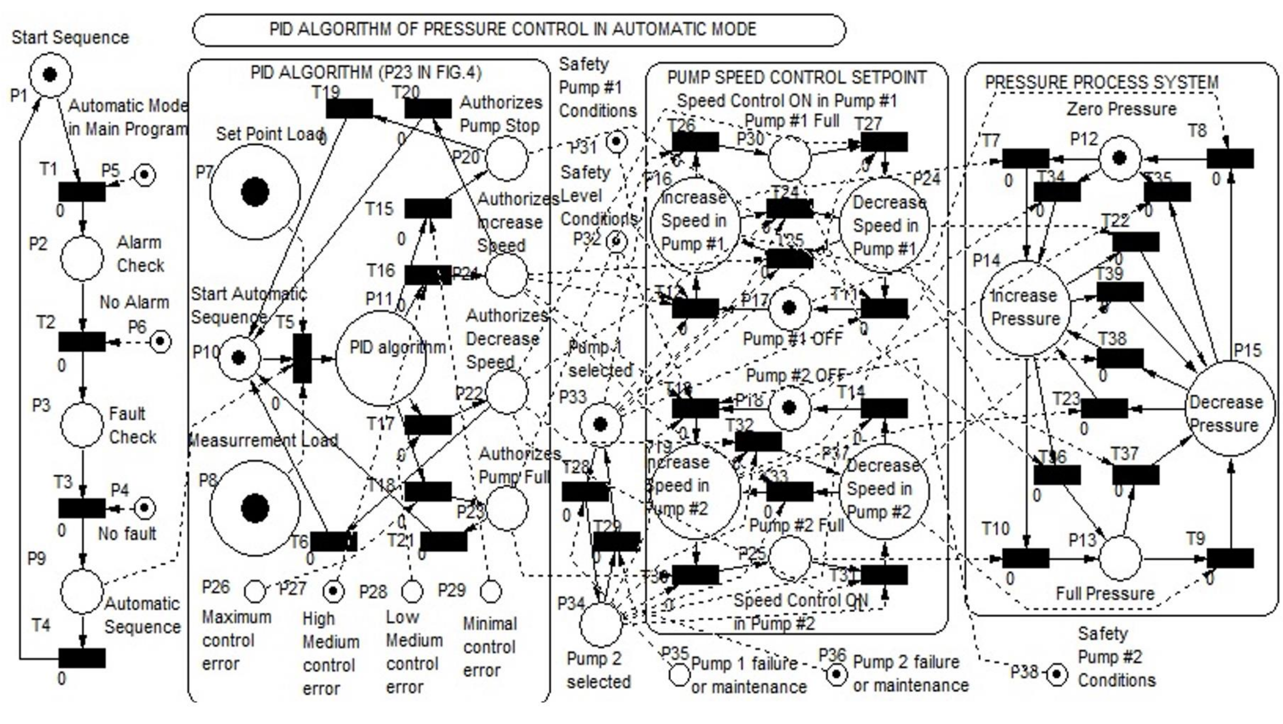

Figure 6. Model of the pressure control function using a PID algorithm.

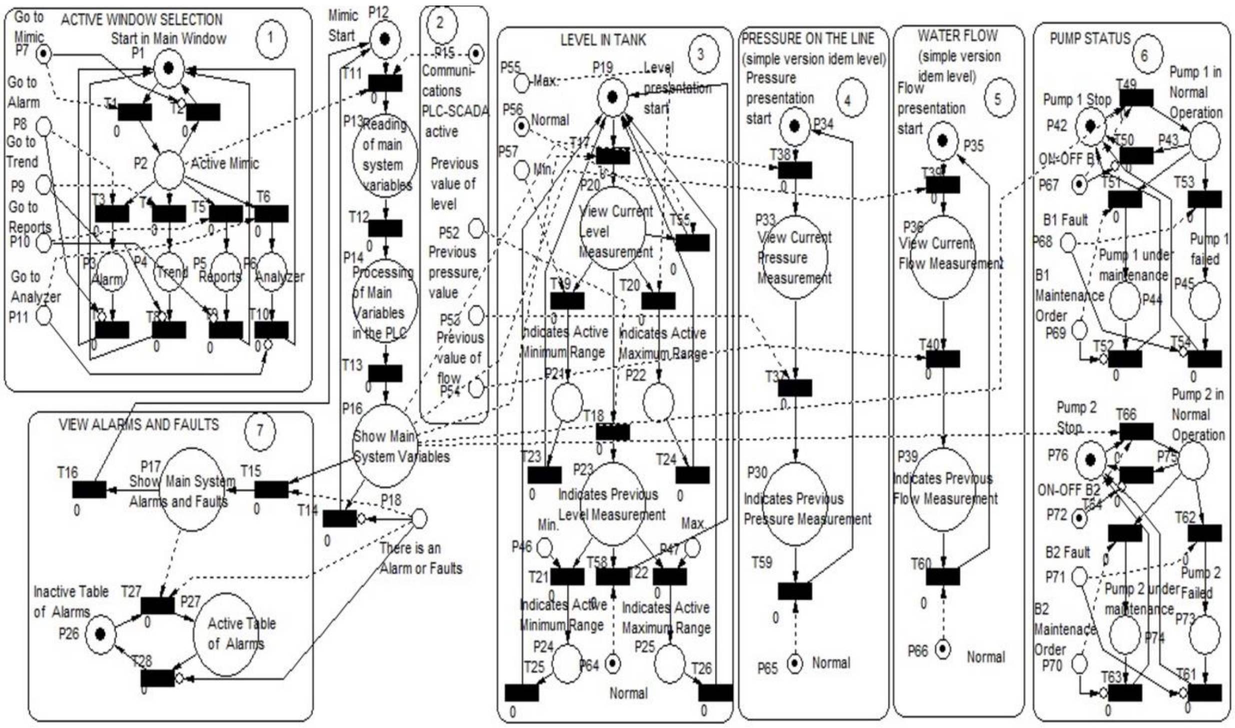

Figure 7. SCADA Mimic model with measurements and process states.

After analyzing the mimic model of the process, it is necessary to characterize the behavior of the system's communications to detect whether the measurements shown on this screen are being managed in real-time or are previous measurements (Model C). Its model in GHENeSys is found in (Acosta, 2015).

When the limit values of the process variables are exceeded, an alarm is triggered, and a fault message is displayed on the Mimic and the SCADA Alarms screen (Model D), considering the type and its possible causes. Each violation of the limit values can cause an entry in the chronological list of events, which can be linked to actions to be taken by the operator or immediate actions by the SCADA (Acosta, 2015).

According to (Benitez-Pina et al., 2017; David & Alla, 2010; Frey & Litz, 1998; Murata, 1989; Silva et al., 2008), the verification consists of checking compliance with the properties of vivacity, limitation, and reversibility. The reduction method (Murata, 1989) was considered to verify the selected models widely used in complex systems. It defines the liveliness of the biggest systems by being grouped to analyze into simpler nets (macro-elements in GHENeSyS) (Benitez-Pina et al., 2017; Silva et al., 2008), which retain the properties of liveliness, reversibility, and limit ability. The uncontrolled model is obtained in each subnet, eliminating the auxiliary control signals. From the underlying net corresponding to the uncontrolled model of each module, the reduction rules, defined in (Murata, 1989), are successively applied, and an elementary net of one place and one transition is reached, which shows that the entire system is well-formed. A cyclical and limited behavior is also ensured by applying place and transition invariants of each matrix associated with the PN model. This allows the study of permissible or unwanted sequences that make possible the correction of erroneous sub-models starting from typical sub-models that were used in other similar subsystems modeled in GHENeSys nets (Acosta, 2015; Benitez-Pina et al., 2017; Silva et al., 2008) thereby demonstrating compliance with the functional and structural properties of PN.

This discrete event control verification process, accepted by the international community (David & Alla, 2010; Miyagui, 1996; Murata, 1989; Ramadge & Wonham, 1989), is applicable in the GHENeSys methodology because it encapsulates the small continuous parts within the discrete model in macro-elements, which represents an advantage concerning the discrete ones (Miyagui, 1996; Ramadge & Wonham, 1989; Raman & Sreenivas, 2021), which do not allow studying the efficiency of integration. It also has an advantage over totally continuous methods (Åström et al., 1996; David & Alla, 2010; Júlvez et al., 2013; Ogata, 2010) because macroelements encapsulate continuous part, and it is not necessary to increase the complexity of the network integrated to a fluidized Petri net (David & Alla, 2010; Hermosilla et al., 2021; Júlvez et al., 2013) with more complex verification algorithms.

The system's functional requirements are validated by simulating all GHENeSys models using dynamic PN simulation tools (visual object Net 2.7 (Drath, 1997) in this case). By this, it is possible to perfect the operation of all the models that later allow an effective translation to application programs based on PLCs. Also, validation using GHENeSys has the same advantages explained for verification.

Then the validated models are translated into the LD, ST, and FBD programming language, which allows for obtaining a hierarchical model at various levels of the application, where each level can be made up of functional units (FU) that are executed through functions implemented in their subnets (one input and one output) called subroutines in the programming language. This guarantees equivalence with the modular structured programming of IEC61131 using functional blocks and permitted routines. The use of macro-elements in GHENsSys PN is compatible with the LD language functional blocks of the PLC (Benitez-Pina et al., 2017; Silva et al., 2008), which is also an advantage with other PN methodologies in the translation to IEC61131 programs.

The EROS platform (Rigó et al., 2018) was used as it is the standardized software in Cuba to implement supervisory systems. It includes an OPC server that communicates through a Client/Server architecture between the SCADA and the PLC and presents all tools for the design and configuration of screens.

The models created in GHENeSys have full compatibility with the possibilities of professional SCADAs, such as EROS software (Rigó et al., 2018). Most other automation design methodologies on PN remain in the local automatics and do not include the different upper levels of integration like GHENeSys.

EROS simulation includes PLC simulation in Modbus communication, and it permits a program validation of the integrated system implementation from PLC to SCADA is the last stage of the design of the proposed methodology that reduces errors before the actual implementation in the plant.

The design of the main screen can be seen in Figure 8 and shows the pumping equipment's behavior, the tank level's status, the pressure in the line, and the rotation speed of the motor. In the case of pumping equipment, the operating status of the four pumps in the Wells and the two in the Pumping System (Work and Reserve) is shown.

Besides, other alarms, trends, reports, and analyzer windows are defined to permit all required SCADA functionalities GHENeSys methodology contributes greatly to the efficient integrated design of SCADA.

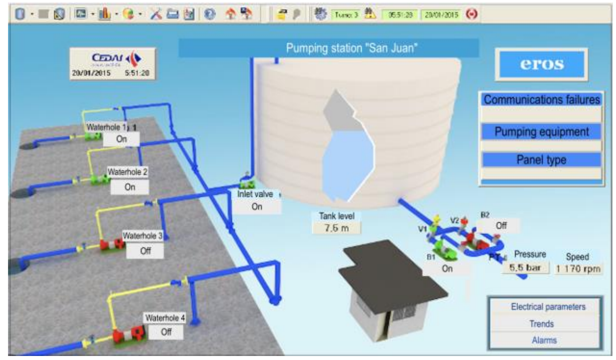

Figure 8. Mimic in EROS that describes the operation of the process.

4. Validation and Discussion of Results

The advantages of the IACS design using the GHENeSys methodology can be summarized as follow:

1- Integrality: It is present from the initial requirements to the implementation of PLC-SCADA and focused on achieving an increase in the efficiency, productivity, and quality of the product or service in an integrative way. The existing methodologies are dedicated only to a part of the process with objectives and, therefore, cannot give an integral vision of the system's efficiency. In this case, the GHeNeSys PN model integrates the continuous control loops of pressure and water flow with the actions of protection, maintenance, water demand management, and intelligent supervision in a simulated way to validate their efficient integration previously.

2- Hierarchical modularity: Has it is center in the hierarchical modular GHENeSys PN models but in all methodology stages: creating the component subsystems, using internal formal models of the automation at each level (continuous and discrete), applying combined verification and validation processes, develop modular translation into programs and configuration of the SCADA with simulated and experimental tests. The other existing methodologies treat these issues with more complexity and partially. In this case, the hierarchical modularity of the GHENeSys models makes it possible to analyze the details individually in the base models (each pressure, flow, velocity, or operation sequence loop is independently validated at the lower level). Then the integration of macro-places is validated at the top level to integrate protections, maintenance, water demand management, and intelligent supervision.

3- IEC61131 Compatibility: It guarantees a high level of applicability of the methodology, but it is also compatible with the initial study and formal design in GHENeSys PN to the actual implementation. The subsystems studied in the functional requirements become modular models encapsulating the lower levels and form part of macro-elements at the higher levels. This hierarchical structure is the same, later created in the PLC program and the SCADA configuration. In this case, this support allows validated models to be directly translated into application programs. For this reason, design validation reduces errors and implementation time, and the efficiency validated in the models is verified with the indicators obtained in the initial tests after their implementation.

The methodology initially develops the adjustment of control loops on MatLab, then includes it in automation sequence inside of hierarchical modular GHENeSys models to follow the verification and validation of the models that guarantee the continuous-discrete integration of all the functions in horizontal and vertical synchronization, achieving efficiency and IEC61131 compatibility. Then, the translation into PLC programs and the configuration of the SCADA are carried out to simulate the integrated system again. The other existing methodologies do not cover all phases from design to implementation, cannot use a combination of simple methods in large parts and complex in a few, are not integrative of all the required functions, and lack compatibility with the programming of the PLC and SCADA. The design of the navigation and operation of the SCADA windows on GHENeSys hierarchical models allows validating the operation, ergonomics, and safety of the IACS, as well as the treatment of alarms, faults, reports, and system maintenance in an integrated way.

The elaboration of a procedure to carry out the integrated formal design-implementation of the IACS of the "San Juan" plant solves the inconvenience of the practical design and isolated design methods of these systems and significantly improves the good operation of the process through the application made.

The system's efficiency quantification must be evaluated after its implementation in the Santiago de Cuba aqueduct. We are currently in the final testing stage of system implementation, following the aqueduct's continuous and discrete functional requirements and from local control to enterprise management. The efficient integration of the models was demonstrated by using the Visual Object Net 2.7 (Drath, 1997) simulation tool from the models using simulated normal or unforeseen situations presented in this article. Still, this tool does not provide graphical results in time axes.

To quantify the efficiency of the design, the results are considered after the implementation tests developed by the Integral Automation Company (CEDAI-Santiago de Cuba), which reports a reduction in design errors by 94% compared to similar projects developed previously. These results were given mainly by the error reduction facilities of the system integration that could be adjusted from the verification and validation of the GHENeSys hierarchical modular model, which also allowed a 65% reduction in the implementation time of the automated system of San Juan Wells. However, due to the time it has been in operation under tests, the necessary data is already available to quantify the efficiency of the system and make a comparison with the previous system, which has allowed a reduction in the rate of ruptures of the aqueduct of 77% to avoid overpressure of water mainly in the nights of low consumption. An energy-saving of 63% has also been obtained from inefficient pumping by controlling the variable speed drive.

5. Conclusions

In the fully integrated design, verification, validation, and implementation of the IACS of the Well pumping San Juan system using the formal GHENeSys modeling, the advantages of this methodology are demonstrated compared to other variants analyzed at the beginning of this work, which only had advantages in a specific type of problem, but not in the IACS integration.

The integrality of the methodology and its total harmony with control systems and the system's alarm, fault, reports, and maintenance treatment functionalities are checked. Also, discrete and continuous algorithms are perfectly integrated with the local operation and, in turn, with the supervisor's operability, efficiency, and security. The reusability of typical sub-models is evidenced in their integration into this application and offers the possibility of extending this IACS or a similar one.

The novelty of the current methodology is to expand this to hybrid GHENeSys applied to the automation of services (such as control of efficient water supply by aqueduct) using macro-elements and auxiliary places with extended arcs from local control to SCADA and automated enterprise management allowing the differentiated verification and validation (discrete methods and/or continuous methods) of each sub-model, and total IEC61131 compatibility, which there are no references in the scientific bibliography consulted.

Conflict of interest

The authors have no conflict of interest to declare.

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References

Acosta, G. (2015). The formal design of the Integrated Automation System for the San Juan Pumping Station using Petri Nets techniques, Master´s Thesis, Automation Department. *Universidad de Oriente*, Santiago de Cuba, Cuba, 2015.

Aguilar, J., Ríos, A., Hidrobo, F., & Cerrada, M. (2013). Sistemas multiagentes y sus aplicaciones en automatización industrial. Talleres Gráficos, Universidad de Los Andes.

Aly, W. H. F., & Kotb, Y. (2018). Towards SDN fault tolerance using petri-nets. In *2018 28th International Telecommunication Networks and Applications Conference (ITNAC)* (pp. 1-3). IEEE. https://doi.org/10.1109/ATNAC.2018.8615188

Åström, K. J., Kheir, N. A., Auslander, D., Cheok, K. C., Franklin, G. F., Masten, M., & Rabins, M. (1996). Control Systems Engineering Education, *Automatica*, *32*(2), 147-166. https://doi.org/10.1016/0005-1098(96)85546-4

Basile, F., Faraut, G., Ferrara, L., & Lesage, J. J. (2020). An optimization-based approach to discover the unobservable behavior of a discrete-event system through interpreted Petri nets. *IEEE Transactions on Automation Science and Engineering*, *17*(2), 784-798. https://doi.org/10.1109/TASE.2019.2944299

Benitez-Pina, I. F., Lamar-Carbonell, S., Silva, R. M. D., Eigi-Miyagi, P., & Silva, J. R. (2017). Design of automatic control system based on unified timed hybrid Petri net. *Dyna*, *84*(200), 80-89. https://doi.org/10.15446/dyna.v84n200.56917.

Borges, M. U., & Lima, E. J. (2018). Conversion methodologies from Signal Interpreted Petri Nets to Ladder Diagram and C language in Arduino. *International Journal of Mechanical Engineering Education, 46*(4), 302-314. https://doi.org/10.1177/0306419018759921

David, R., & Alla, H. (2010). *Discrete, continuous, and hybrid Petri nets* (Vol. 1, pp. 17-130). Berlin: Springer. https://doi.org/10.1007/b138130

Drath, R. (1997). A mathematical approach to describing a class of hybrid systems. In *Proceedings of 5th International Workshop on Parallel and Distributed Real-Time Systems and 3rd Workshop on Object-Oriented Real-Time Systems* (pp. 228-232). IEEE. https://doi.org/10.1109/WPDRTS.1997.637984

Frey, G., & Litz, L. (1998). Verification and validation of control algorithms by coupling of interpreted petri nets. In *SMC'98 Conference Proceedings. 1998 IEEE International Conference on Systems, Man, and Cybernetics,* (Vol. 1, pp. 7-12). IEEE. https://doi.org/10.1109/ICSMC.1998.725375

Hermosilla, D. M., Codorniú, R. T., Baracaldo, R. L., Zamora, R. S., Rodriguez, D. D., Albuerne, Y. L., & Álvarez, J. R. N. (2021). Shallow convolutional network excel for classifying motor imagery EEG in BCI applications. *IEEE Access*, *9*, 98275-98286. https://doi.org/10.1109/ACCESS.2021.3091399

Holloway, L. E., Krogh, B. H., & Giua, A. (1997), A. Survey of Petri Net Methods for Controlled Discrete Event Systems. *Discrete Event Dynamic Systems*, *7*, 151-190. https://doi.org/10.1023/A:1008271916548

Jakovljevic, Z., Lesi, V., Mitrovic, S., & Pajic, M. (2019). Distributing sequential control for manufacturing automation systems. *IEEE Transactions on Control Systems Technology*, *28*(4), 1586-1594. https://doi.org/10.1109/TCST.2019.2912776

Júlvez, J., Vázquez, C. R., Mahulea, C., & Silva, M. (2013). Continuous Petri nets: controllability and control. *Control of Discrete-Event Systems: Automata and Petri Net Perspectives*, 407-428. https://doi.org/10.1007/978-1-4471-4276-8

Kaid, H., Al-Ahmari, A., & Li, Z. (2020). Colored resource-oriented Petri net based ladder diagrams for PLC implementation in reconfigurable manufacturing systems. *IEEE Access*, *8*, 217573-217591. https://doi.org/10.1109/ACCESS.2020.3041408

Kanamaru, H. (2020). Requirements for IT/OT Cooperation in Safe and Secure IACS. In *2020 59th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)* (pp. 39-44). IEEE. https://doi.org/10.23919/SICE48898.2020.9240295

León, A. A. S., & Alvarez, J. R. N. (2019). 1D convolutional neural network for detecting ventricular heartbeats. *IEEE Latin America Transactions*, *17*(12), 1970-1977. https://doi.org/10.1109/TLA.2019.9011541

Li, X., Xing, K., Zhou, M., Wang, X., & Wu, Y. (2019). Modified dynamic programming algorithm for optimization of total energy consumption in flexible manufacturing systems. *IEEE Transactions on Automation Science and Engineering*, *16*(2), 691-705. https://doi.org/10.1109/TASE.2018.2852722

Lin, W., Luo, J. L., Zhou, J. Z., Huang, Y. S., & Zhou, M. C. (2016). Scheduling and control of batch chemical processes with timed Petri nets. In *2016 IEEE International Conference on Automation Science and Engineering (CASE)* (pp. 421-426). IEEE. https://doi.org/10.1109/COASE.2016.7743436

Luo, J., Zhang, Q., Chen, X., & Zhou, M. (2018). Modeling and race detection of ladder diagrams via ordinary Petri nets. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *48*(7), 1166-1176. https://doi.org/10.1109/TSMC.2016.2647219

Lutz-Ley, A., & López-Mellado, E. (2018). Stability analysis of discrete event systems modeled by Petri nets using unfoldings. *IEEE Transactions on Automation Science and Engineering*, *15*(4), 1964-1971. https://doi.org/10.1109/TASE.2018.2830385

Miyagi, P. E. (1996). Controle programável: fundamentos do controle de sistemas a eventos discretos. Editora Blucher.

Murata, T. (1989). Petri nets: Properties, analysis and applications. *Proceedings of the IEEE*, *77*(4), 541-580. https://doi.org/10.1109/5.24143

Nuñez, J., Pina, I. F. B., Martínez, A. R., Pérez, S. D., & de Oliveira, D. L. (2019). Tools for the Implementation of a SCADA System in a Desalination Process. *IEEE Latin America Transactions*, *17*(11), 1858-1864. https://doi.org/10.1109/TLA.2019.8986424

Nuñez, J. R., Mestre, J., Cabello, J. J., Dominguez, H., Fong, J., Peña, L., ... & De Oliveira, D. (2020). Design of a fuzzy controller for a hybrid generation system. In *IOP Conference Series: Materials Science and Engineering* (Vol. 844, No. 1, p. 012017). IOP Publishing. https://doi.org/10.1088/1757-899X/844/1/012017

Ogata, K. (2010). Ingeniería de Control Moderna, 5th ed, Editorial: Pearson Prentice Hall.

Ramadge, P. J., & Wonham, W. M. (1989). The control of discrete event systems. *Proceedings of the IEEE*, *77*(1), 81-98. https://doi.org/10.1109/5.21072

Raman, A., & Sreenivas, R. S. (2021). Liveness enforcing supervisory policies tolerant to controllability failures for discrete-event systems modeled by Petri Nets. *Automatica*, *125*, 109430. https://doi.org/10.1016/j.automatica.2020.109430

Reynard, S., Gomis-Bellmunt, O., Sudrià-Andreu, A., Boix-Aragonès, O., & Benítez-Pina, I. (2008). Flexible manufacturing cell SCADA system for educational purposes. *Computer Applications in Engineering Education*, *16*(1), 21-30. https://doi.org/10.1002/cae.20115

Rigó, S. E. S., Laguardia, A. S. M., & Mederos, O. P. (2018). Web Client and SCADA Applications for Monitoring the “Cayo Santa María”. Isolated Electric System. Sistemas & Telemática, 16(47), 59-70.

Silva, J. R., Benítez, I., Villafruela, L., Gomis, O., & Sudrià, A. (2008). Modeling extended Petri nets compatible with GHENeSys IEC61131 for industrial automation. *The International Journal of Advanced Manufacturing Technology*, *36*, 1180-1190. https://doi.org/10.1007/s00170-006-0924-5

Silva, J. R., Poli, M. A., Soares, C., & Mendez, J. (2010). A holonic approach to the integration of automated systems, *ABCM Symposium Series in Mechatronics*, 4, 442-450. https://hdl.handle.net/1822/18108

Theis, J., Mokhtarian, I., & Darabi, H. (2019). Process mining of programmable logic controllers: Input/output event logs. In *2019 IEEE 15th International Conference on Automation Science and Engineering (CASE)* (pp. 216-221). IEEE. https://doi.org/10.1109/COASE.2019.8842900

Uzam, M. U. R. A. T., & Jones, A. H. (1998). Discrete event control system design using automation Petri nets and their ladder diagram implementation. *The International Journal of Advanced Manufacturing Technology*, *14*, 716-728. https://doi.org/10.1007/BF01438224

Yue, H., Xu, S., Zhou, G., Hu, H., Guo, Y., & Zhang, J. (2019). Estimation of least-cost transition firing sequences in labeled Petri nets by using basis reachability graph. *IEEE Access*, *7*, 165387-165398. https://doi.org/10.1109/ACCESS.2019.2952056