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Modelling and verification of an automatic controller for a water treatment mixing tank

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ABSTRACT

A modern control framework for a mixing tank is demonstrated. Numerous preferences, and the ranges needed to ensure the quality of the framework need to be determined, to obtain a fast reaction time, lessen the cost of execution and support, and finally diminish harm. In this paper, the display and controller for a programmable synthetic substance water treatment blender for industrial tanks is introduced. The Petri net method is utilized to demonstrate and check the instruments. The system is controlled and implemented using sequential control system (SCS). Each block of the sequential control system is modelled and verified using the Petri net MATLAB 2008a tool-box. The method for the coupling of the hardware and software is described in detail and a simulation carried out to check its validity. A programmable logic controller (PLC) is used in the model for the control of sequential actions, which actually minimizes the cost and provides high reliability. With regard to energy consumption, the study apparently found that lower percentages of energy consumptions between using and not using it with few occurrences of higher values.

Keywords: Water treatment; Mixing tank; Modelling; Petri net; Sequential system control

1. Introduction

1.1. Literature overview

Groundwater quality has long been studied to find better ways to manage media filters for water treatment [1]. Advancements in technology and increasing demand has led to the development of automatic systems for the supervision and control of industrial water treatment systems [2]. One commonly adopted control strategy is the sequential control system is designed to control a process which continues from one step to another when certain conditions related to the nature of the input and output of the products are met. Such sequential control systems have been adopted for use in: assembly lines where products are assembled step by step in a sequential manner; for conveyor systems that convey products batch by batch; industrial robotics; power protection system; motor starting; and many other areas.

The sequential control system (SCS) consists of several module components that are coupled together to form a complete control system (i.e., detection devices, monitoring devices, control operation devices, sequential control action devices, control command devices, etc.). It is more convenient to model most of the devices used in sequential control systems using discrete control tools (e.g., Petri net, automata) due to the nature of their operations.

For many years, industrial systems have relied on the use of the proportional integral controllers (PI) and proportional integral derivative controllers (PID). However, the sluggish response time of these controllers can lead to

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degradation of functionality and at the same time PI or PID controllers are very expensive and not so efficient for large systems. Such problems can be overcome by using programmable logic controllers (PLC).

Modelling and control of modern, complex systems such as traffic control systems, water treatment process control, and robotics systems remains a big challenge to control engineers. The major goal of control engineering is the ability to ensure optimal and reliable operation of the system while minimizing the cost of production. Proper modelling tools remain an open problem for control engineers [3].

The PLC has recently become much more widely used for automated industrial control to significantly enhance the production rate, use raw materials efficiently, ensure system reliability and obtain many other benefits that cannot even be compared to high quality workmanship by humans [4]. Basically, the PLC is an automatic and sequential control device that receives input (i.e. in the form of signals from sensor devices, control action devices, control system devices, etc.), information which is stored and processed in the memory and its processor, respectively, and then output as a logic signal to switching devices, timing and counting devices arithmetic and data handling devices, and so on [5].

These days, PLC techniques are widely used in large size industrial application, but programming and analysis is complicated, and issues of safety in relation to both life and property due critical software failure must be given more attention in the design model. Therefore, for any industrial system design modelling must be carried out to verify whether it meets the desire specifications prior to implementation. Presently, the tools most often used for modelling and system verification before implementation are Petri nets [6–8], time automata [9,10], and modeling from time attributes [11,12].

In this study, the Petri net is used as a tool to model the sequential control system for water treatment mixing tanks in an industrial process. The model is verified before its implementation into a PLC based on the special properties of petri nets such as boundedness, liveness and safeness. A ladder diagram of the model is presented for implementation.

1.2. Basic features of the Petri net

The Petri net, likewise acknowledged as a place/transition (PT) net, is one of the numerous mathematical modeling languages for the representation of scattered systems. In this section, we briefly review the Petri net definitions; a more detailed description can be found in [13]. Petri nets are state-transition regularities that spread a level of nets described elementary nets by Rozenburg, and Engelfriet (1998) [14].

Definition 1. A net is a triple N = (P, T, F) where:

1. P and T are disjoint limited sets of points and shifts, individually.
2. $F \subset (P \times T) \cap (T \times P)$ is a countable set of arcs (or course associations).

Definition 2. Given a net N = (P, T, F), an arrangement is a countable set C so that $C \subseteq P$.

Definition 3. An elementary net is a net of the form EN = (N, C) in which:

1. N = (P, T, F) is a countable net.
2. C is so that $C \subseteq P$ is an arrangement .

Definition 4. A Petri net is a countable net of the form PN = (N, M, W), that stretches the fundamental net such that:

1. N = (P, T, F) is a countable net.
2. $M : P \to Z$ is a countable place multiset, where Z is a countable set. M spreads the concept of a configuration and is ordinarily depicted with the associate to Petri net plans as a labeling.
3. $W : F \to Z$ is an arc countable multiset, so that the number (or density) for each arc is a ratio of the arc multiplicity.

If a Petri net is commensurate to an elementary net, then Z can be the countable set {0,1} and these elements in P that map to 1 under M form an arrangement. The Petri net is comprised of a four tuple, where *P* and *T* are finite and non-empty sets. *P* is a set of places and *T* is a set of transitions with. is called a flow relation of the net, represented by directed arcs with arrows from places to transitions or transitions to places. Places are graphically represented by circles while transitions are graphically represented by bars or squares boxes. is a mapping that assigns a weight to an arc.

Let be a node in . The preset of is denoted by $^{\bullet}x$, is defined as $^{\bullet}x$ and the postset as $x^{\bullet}$. Let be a transition in at a state.

Transition is said to be enables if an enabled transition *t* can fire, leading to a new state. A place is said to be k-bounded if. A net is said to be -bounded if any place is -bounded. A place is said to be safe if it is one-bounded. A net system is said to be safe if all of its places are safe. A net system is said to be live if is live at.

2. System modelling

2.1. Sequential control system

A control arrangement in which the specific measures are concocted in a predestined order, succession from one sequence measure to the next being dependent on defined conditions being performed. Automatic control of water treatment mixer tanks for industrial application comprises several devices i.e. detection devices, monitoring devices, sequential system devices (i.e. PLC), devices for control operations, and control system. Fig. 1 shows a functional block diagram of a sequential control system with symbiotic organisms search. Each functional block interrelates with the control system either directly or indirectly.

Algorithm. Symbiotic organisms search

1: Initialization (*ecosize*)
2: While terminating criteria is not achieved
3: Iteration = Iteration + 1
4: For all solutions 1 from 1 to *ecosize*
5: Mutualism phase
6: Select a random solution X_j, $X_j \neq X_i$
7: Calculate the mutual-relationship and benefit-factor

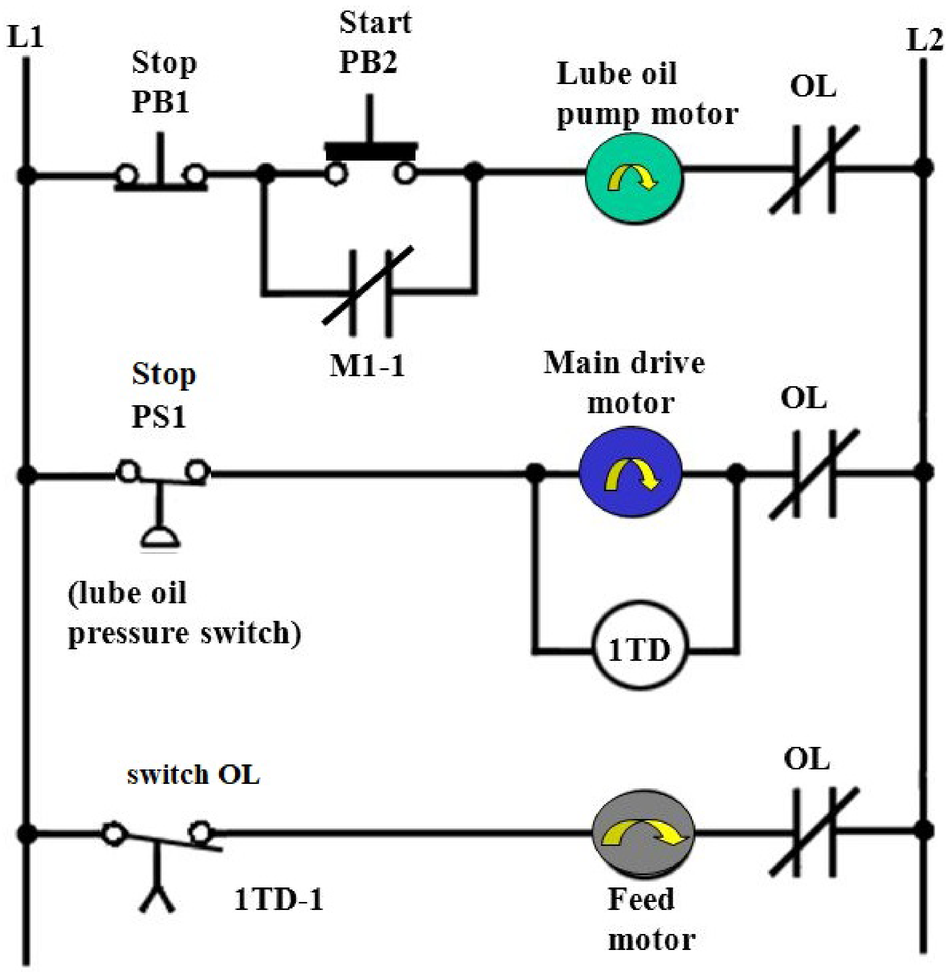

Fig. 1. Basic configuration of sequential control system.

8: Modify X_i and X_j
9: If the modified solution is better, then the original will be replaced
10: FE = FE + 2
11: Commensalism phase
12: Select a random solution X_j, $X_j \neq X_i$
13: Modify X_i according to X_j
14: If the modified solution is better, then the original will be replaced
15: FE = FE + 1
16: Parasitism phase
17: Select a random solution X_j, $X_j \neq X_i$
18: Create a mutated solution of X_i
19: If the mutated solution is better than X_j, then X_j will be replaced
20: FE = FE + 1

Proper modeling of each block diagram in the basic configuration of the sequential control system is required to meet the desired specification. The complete model for automatic control of a water treatment mixing tank includes both hardware and software, and both of these elements are modelled using Petri net software for analysis and verification. The hardware used in this system include the limit switch for detection devices, push button switch used by an operator, electromagnetic valves controlling device operation, and lamps for the monitoring device while the software includes the control of sequential action (by the PLC) that governs the interrelation between modules. Both hardware and software can secure a discrete finite state, making the model easier to simulate using Petri nets.

2.2. Control system specification

Fig 2. Shows an industrial tank to be filled with two chemicals, mixed and then drained (automatically controlled water treatment mixing tank). When the start button is pressed, the PLC and lamp 1 are in the ON state. LS1 and LS2 are responsible for sending information about the level of water treatment inside the tank to the PLC. If the level of the mixed chemicals inside the tank is at the lower limit (L), LS1 is OFF and LS2 is ON, and electromagnetic valves (V1) and (V2) are OPEN to let the two chemicals flow into the tank. At the same time lamp 2 is in the ON state, indicating that chemicals are flowing into the tanks. When the level of the chemicals inside the tank reaches one-third of the capacity of the tank (N) the mixer motor is turned ON along

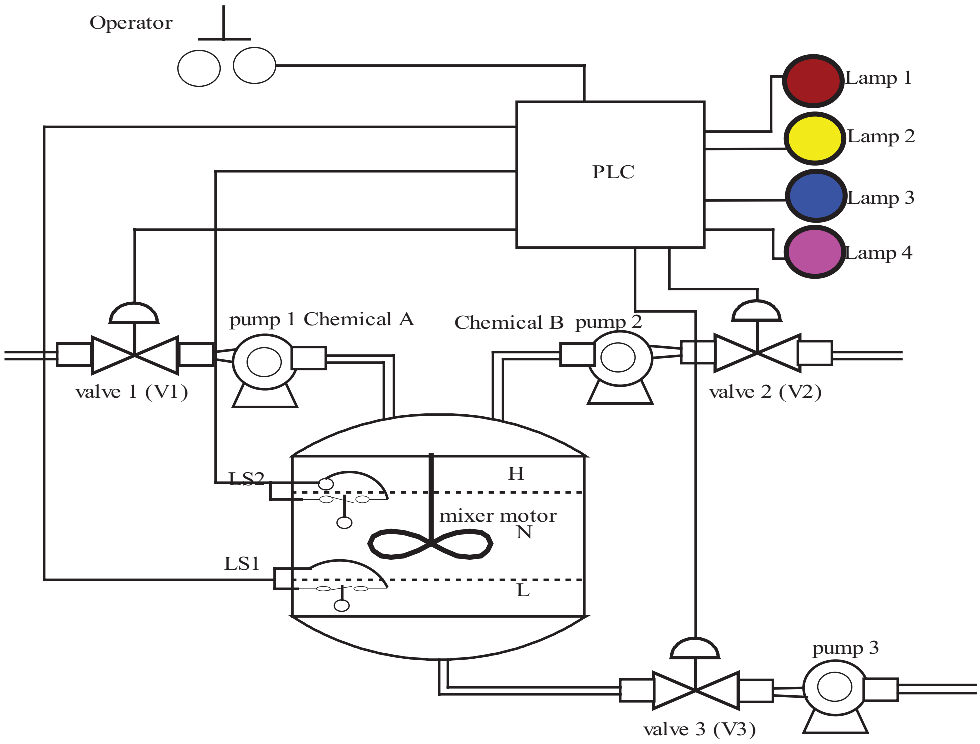

Fig. 2. Chemical water treatment mixing tank.

with lamp 3, to indicate the mixing state. If the level of the chemical reaches the high level (H), LS2 is turned OFF and LS1 is turned ON, valves (V1) and (V2) are turned OFF and lamp 2 is also turned OFF. At that instant an on-delay timer is triggered by the PLC to time when the chemicals can be expected to be in a homogenous mixed state. When the time has elapse, the mixer motor is turned OFF and lamp 3 is also turned OFF. Immediately when the mixer pump is OFF, lamp 4 is turned ON and electromagnetic valve (V3) is Open. The mixed chemicals in the tank then start to drain out until reaching the lower Level (L), then LS1 is turned OFF and LS2 is turned ON. This again turns ON valves (V1) and (V2) and the process repeats. The process is stopped by pushing a button to stop the PLC and the whole system comes to a standstill.

2.3. System modelling and analysis

The desired specifications as described in section II(c) and illustrated in Fig. 2 are translated into a control problem for modelling. In the above description we have two kind of specifications, namely hardware specifications and software specifications. The hardware specifications involve the physical devices incorporated into the control system and the software specifications involve the PLC for automation of the process. Almost all the physical devices will either be ON or OFF while the electromagnetic valves will be either OPEN or CLOSED. All of them can be modelled in the same manner using the Petri net method.

Fig. 3 shows a model of the limit switch, including indicator lamps and electromagnetics valves that can be used to secure two states. The model can be easily verified. Here

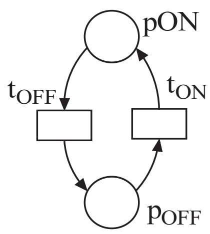

Fig. 3. Switch model.

p1 represents the OFF state, and p2 represents the ON state; t1 represents the switching of the mechanism from the OFF state to the ON state, and t2 represents the switching of the mechanism from the ON state to the OFF state. The black dot represents the signal transition from the OFF state to the ON state, similarly for the electromagnetic valves, where ON and OFF can be changed to OPEN and CLOSED, respectively.

We now analyze the operation illustrated in Fig. 3. Initially the model is in the OFF state, t1 is enable to fire while t2 is disabled in that state. If t1 fires it changes the state of the model from the OFF to the ON state. In this state, t1 is disabled and t2 is enables, meaning that t2 can fire. If t2 fires, its current state changes to the initial state. This process is repeated as long as there is a "token" in any one of the places. This consistent with the ON and OFF operation and CLOSED and OPEN operation of the limit switch and electromagnetic valve, respectively.

Fig. 5 shows the specification model of the software part (i.e. the PLC) and the hardware specifications. The software model uses 11 states to derive the required specifications.

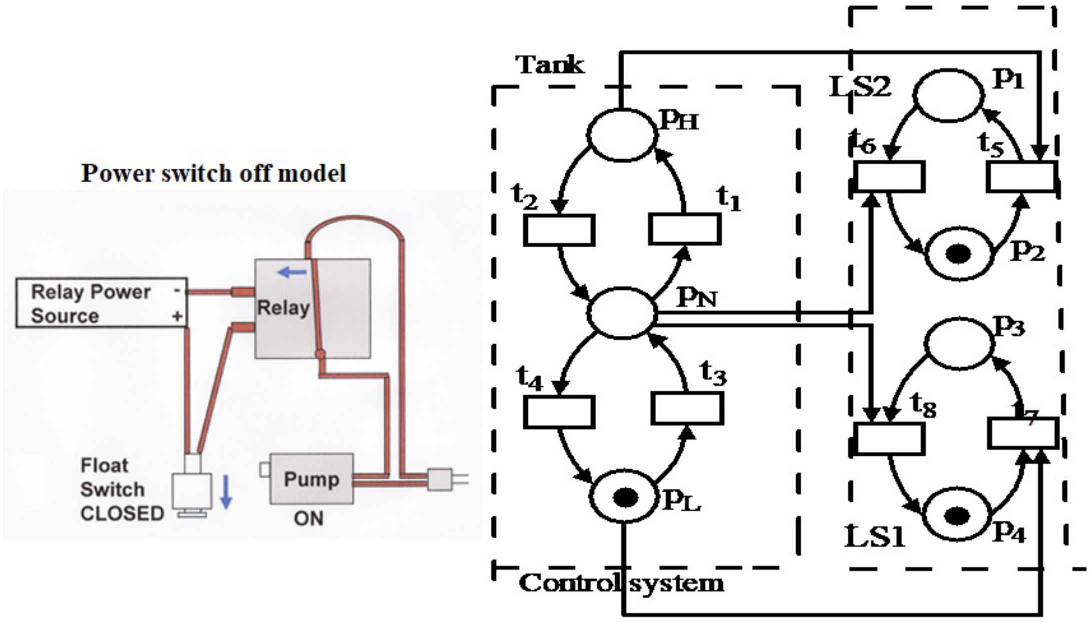

Fig. 4. Limit switch with tank model from.

When the push button switch is press to the ON state, T0 is enabled, but all other transitions are disabled; if T0 is fired the state moves to S0. In that state lamp 1 is ON and T1 is enabled only if LS1 is OFF, while all other transitions are disabled. If T1 fired, the model enters another state, S1. In that state, lamp 1 is turned OFF, lamp 2 is turned ON and T2 can be enabled only if LS2 is ON. If T2 is enabled it changes the state from S1 to S2, in which case electromagnetic valves (V1) and (V2) are opened. T3 is enabled while all other transitions are disabled. if T3 is fired the state changes to S3 and S4, indicating the flow of chemicals into the tank. T4 is enabled only if the level of chemicals in the tank is at N (two-third of the capacity of the tank). I T4 enabled, another state is entered, S5, in which case lamp 3 and the mixer pump are turned ON. If T5 is enabled, another state is entered, S6, which indicates mixing. T6 can be enable only if level of the mixed chemicals in the tank is at H. If T6 is enabled, another state, S7, is entered which turns OFF electromagnetic valves (V1) and (V2). Lamp 2 is also turned OFF and the on-delay timer turned ON. T7 can only be enabled if the on-delay timer is OFF. When T7 is enabled another state, S8, is entered in which the mixer pump is turned OFF, lamp 3 is turned OFF and electromagnetic valve (V3) is OPEN. When T8 is enabled another state is entered, S9, for draining the mixed chemicals from the tank. T9 can be enabled only when LS2 is ON. If T9 is enabled, another state, S10, is entered where the electromagnetic valve (V3) is OFF. The process is automatically repeated until the push button switch on the PLC is turned OFF.

2.4. Module coupling

This section presents the methodology for coupling sub-modules to obtain a complete control model for the automatic control of a chemical water treatment mixing tank.

The complete model for automatic control of a chemical water treatment mixing tank is shown in Fig. 5. The modelled hardware and software need to be correctly coupled to communicate with each to attain the optimal control actions. This is achieved by connecting each transition to its immediate state. The circulation of the “token” in the model signifies the change in state.

Consider the detection device responsible for determining the water level in the tanks. It communicates with the sequential control device (PLC) and control system: it receives a signal from the control system device about the water treatment level of mixed chemicals at different states, e.g. high (pH), medium (pM) or low (pL). The information is conveyed to the sequential control devices to take action to OPEN or CLOSE the electromagnetic valves (V1), (V2) and (V3).

The control operation device receives signal information from the sequential action device (PLC) which impacts the information sent to the control system device. The signal is taken from the states (output) of the PLC and fed into the decidable transitions (input) for electromagnetic valves (V1), (V2), and (V3). In turn V1, V2 and V3 impact the information sent to the control system. The signal in its states (output) is fed into the transitions (input) of the control system.

3. SYSTEM verification

We now discuss the case of the pump mixer as it interrelates with the PLC and the ON-delay timer. Signal information is received from the PLC and fed to the pump mixer to decide whether it will be turned ON or OFF. The signal is taken from the states (output) of the PLC and fed into the pump mixer transitions (input).

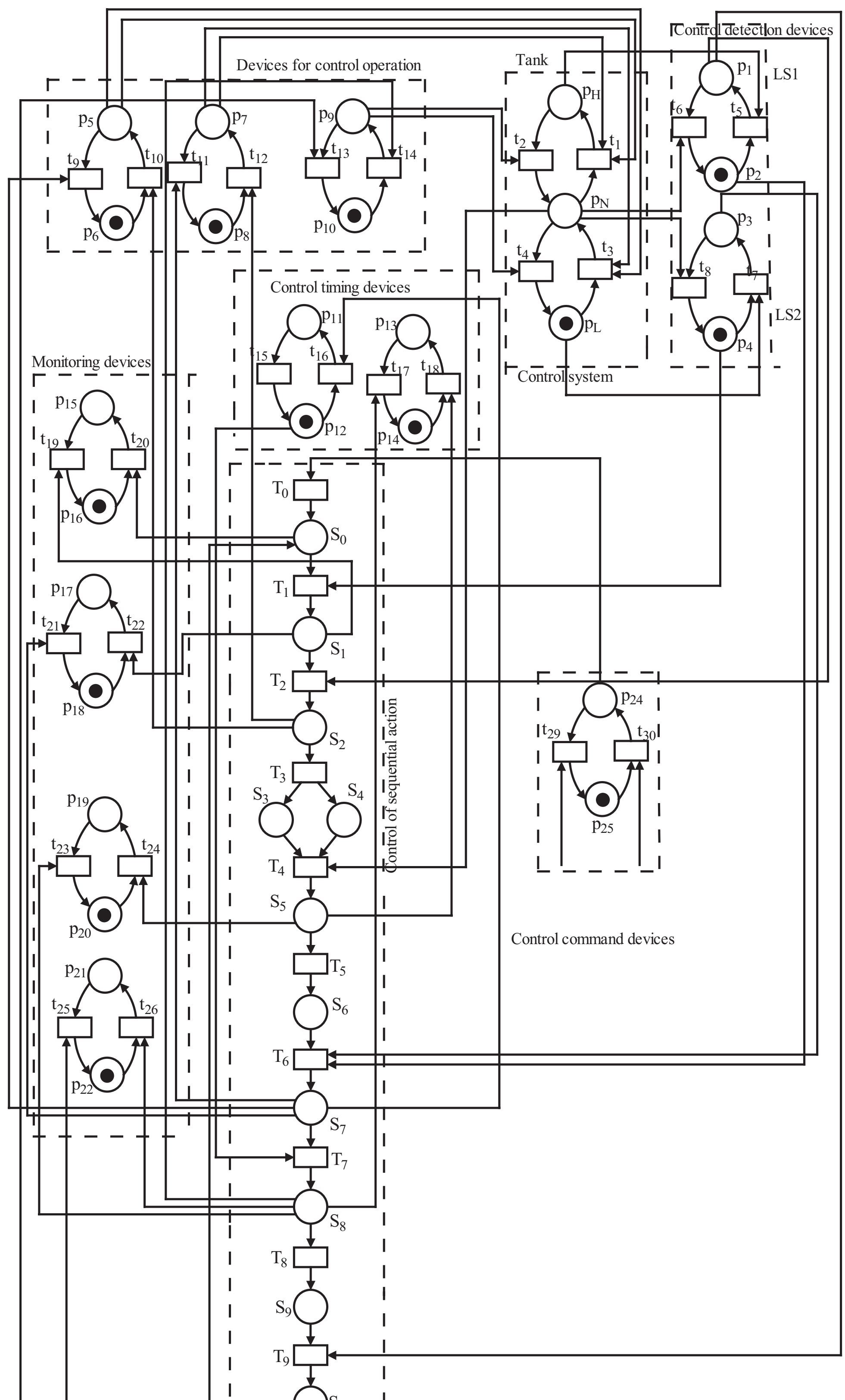

Fig. 5. Complete model for automatic control of a chemical water treatment mixing tank.

Table 1
Meaning of the symbols used in the hardware model

Input	Usual meaning	Output	Usual meaning
t1	Switch from N to H	pN 2/3	Chemicals filling at least capacity of the tank
t2	Switch from H to N	pH	Chemicals at high level L2 is turned ON
t3	Switch from L to N	pL	Chemicals at low level
t4	Switch from N to L		
t5	Turn LS1 ON	p1	LS1 is ON
t6	Turn LS1 OFF	p2	LS1 is OFF
t7	Turn LS2 ON	p3	LS2 is ON
t8	Turn LS2 OFF	p4	LS2 is OFF
t9	CLOSE valve V1	p5	Valve V1 is OPEN
t10	OPEN valve V1	p6	Valves V1 is CLOSED
t11	CLOSE valve V2	p7	Valve V2 is OPEN
t12	OPEN valve V2	p8	Valve V2 is CLOSED
t13	CLOSE valve V3	p9	Valve V3 is OPEN
t14	OPEN valve V3	p10	Valve V3 is CLOSED
t15	Turn OFF timer	p11	Timer is ON (working)
t16	Turn ON timer	p12	Timer is OFF
t17	Turn OFF mixer motor	p13	Mixer motor is working
t18	Turn ON mixer motor	p14	Mixer motor is not working
t19	Turn OFF Lamp 1	p15	Lamp 1 is ON
t20	Turn ON Lamp 1	p16	Lamp 1 is OFF
t21	Turn OFF Lamp 2	p17	Lamp 2 is ON
t22	Turn ON Lamp 2	p18	Lamp 2 is OFF
t23	Turn OFF Lamp 3	p19	Lamp 3 is ON
t24	Turn ON Lamp 3	p20	Lamp 3 is OFF
t25	Turn OFF Lamp 4	p21	Lamp 4 is ON
t26	Turn ON Lamp 4	p22	Lamp 4 is OFF
t27	Turn OFF PLC	p24	PLC is ON
t28	Turn ON PLC	p25	PLC is OFF

Table 2
Usual meaning of the symbols use in the software model

Input	Usual meaning	Output	Usual meaning
T0	Push button	S0	L1 is turned ON
T1	LS2 is turned OFF	S1	L1 is turned OFF, L2 is turned ON
T2	LS1 is turned ON	S2	Valves V1 and V2 is OPEN
T3	1 is True	S3	Chemical A is flowing
		S4	Chemical B is flowing
T4	Chemical level at N	S5	Mixer is turned ON, Lamp 3 is turned ON
T5	1 is True	S6	Mixing the chemicals
T6	LS1 is turned ON	S7	Valves V1 and V2 are CLOSED Lamp 2 is turned OFF
T7	Timer is turned OFF	S8	Mixer motor is turned OFF Lamp 3 is turned OFF Valve 3 is OPEN Lamp 4 is turned ON
T8	LS1 is turned OFF	S9	Chemical is draining
T9	LS2 is turned ON	S10	Valve 3 is CLOSED Lamp 4 is turned OFF Lamp 1 is turned ON

Table 3
Two-dimensional system verification

Known length	Measured length	Known area	Measured area	Length error	Area error	Efficiency
0.30000	0.30000	0.16000	0.16010	0.00000	0.04000	96.00%
0.20000	0.20010	0.04000	0.04000	0.05000	0.00000	95.00%
0.10000	0.10000	0.02000	0.02001	0.00000	0.05000	95.00%
0.09000	0.09000	0.00500	0.00500	0.02000	0.06000	92.00%
0.07000	0.07010	0.00500	0.00500	0.00700	0.06000	93.30%
0.06000	0.06000	0.00320	0.00320	0.00000	0.00000	100.00%
0.05000	0.05000	0.00180	0.00180	0.04000	0.04000	92.00%
0.04000	0.01000	0.00800	0.00801	0.08000	0.08000	84.00%
0.03000	0.03000	0.00800	0.00801	0.00000	0.01000	99.00%
0.02000	0.02000	0.00400	0.00400	0.00000	0.08000	92.00%

For timing devices, the system receives information regarding the output (state) of the PLC and this is fed in as input (transition). The output (state) information is fed into the PLC to perform action on the pump mixer. Lastly, the monitoring devices only communicate with the PLC and the operator. Information is received about the state (output) of the PLC to act as input (transitions). The information is utilized to output a proper decision (states) to the operator.

The proper analysis and verification of the model before implementation is equally important. It is essential that the model can work with the desired specification and provide high effectiveness. The Petri net modelling and mathematical tools are used to verify the proposed model. Three important properties are verified, "liveness" to guarantee the absence of the blocking (deadlock) state in the proposed model, the "boundedness" of the model and finally the "safeness". All checking is done using the Petri net toolbox for MATLAB 2008a.

For liveness, at the moment when the ON button is pushed by the operator, the PLC receives a token and the whole system keeps working. At each state of the proposed model, at least one transition is enabled, and the token keep circulating to signify its liveness. Since the system is live, there is not blocking state in the model, and this is in line with the simulation results obtained using the Petri net toolbox for MATLAB 2008a.

The boundedness can be easily checked by considering each sub-model. P-invariants form in each sub model, meaning that the token circulation in each sub model is constant i.e., where, it indicates that places and can never have token at the same time, the token is either at place or at place; this exactly show the boundedness properties. So also and. The model simulated results obtained using the Petri net tool box for MATLAB 2008a verify the boundedness of the whole system.

Safeness implies that each place or state in each sub model can only accommodate one token at a time with agreement of two-dimensional system verification in Table 3, and the proposed model complies with this definition. When the whole system is simulated using integrated net analyzer (INA), the model is safe.

4. Implementation of the software specifications

This section describes the software implementation for the PLC needed to accomplish the automated control tasks using a ladder diagram. The PLC code is easily written based on the ladder diagram structure. The advantage of the Petri net tool is that, beyond modelling and verification, it also very easy to transform the Petri net into a ladder diagram. Fig. 6 shows the equivalent ladder diagram of a complete model of the automatic control system for the chemical water treatment mixing tank.

The system is controlled and implemented using sequential control system (SCS). After implementation and verification of the Petri net simulation tool box for MATLAB 2008a for water treatment mixing tank, results have been shown by the comparison with and without PLC. With regard to energy consumption, a greater difference in the results may be noticed (Fig. 7). The use of the application made it possible to consume considerably less energy than when not using it, with few occurrences of higher values. It was possible due to temperature adjustments made by the application, which allowed an increase in the temperature in situations where it was adequate, but consumption was high.

4. Conclusion

This paper presents an automatic control method for chemical water treatment mixing in an industrial tank. The Petri net simulation tool box for MATLAB 2008a is used for modelling and verification. The results show that there is an absence of blocking states in the model. The implementation follows a sequential control system strategy, as shown in Fig. 6, that automatically controls the whole system.

The proposed model is effectively verified and high system reliability derived, ensuring low cost implementation and ease of maintenance, efficient utilization of raw materials, and significant enhancement of homogeneous mixing of the chemicals. The model could be used in many industrial devices in a variety of areas such as in the pharmaceutical industry, biomedical industry, fertilizer manufacture, oil refineries, and many more.

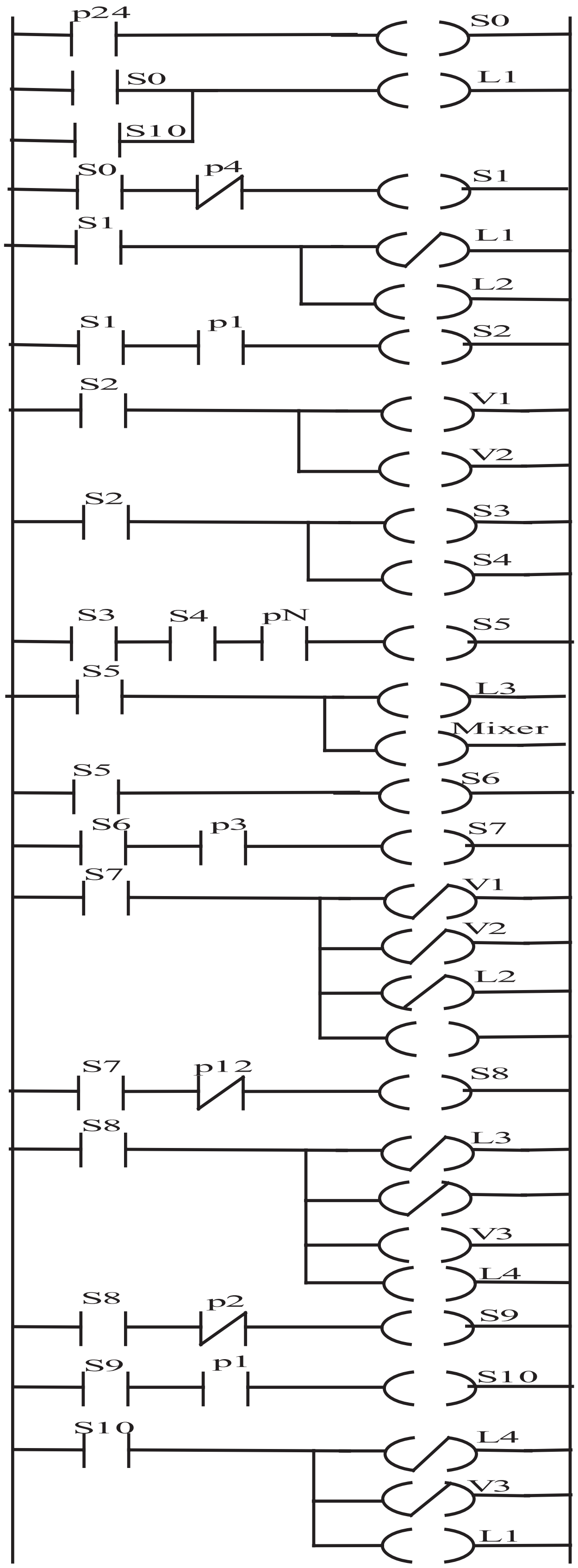

Fig. 6. A Ladder diagram for the complete model.

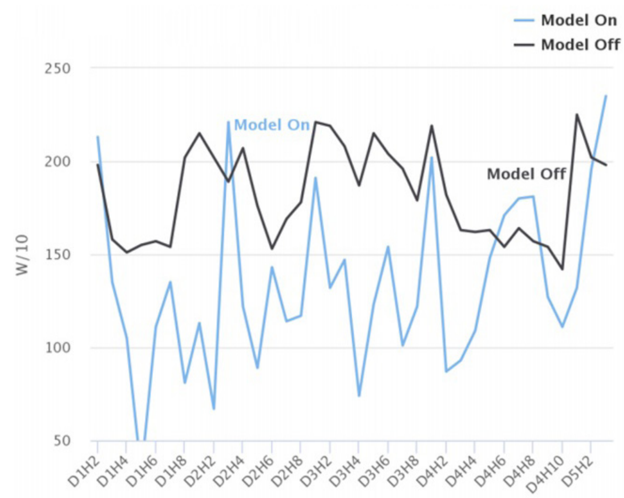

Fig. 7. Consumption on x axis of time scale using and not using the PLC.

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