Deadlock Control Design and PLC Implementation of Automated Manufacturing Systems

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Abstract

Petri nets are an effective way to model, analyze, and control deadlocks in automated manufacturing systems (AMSs). The need for an effective design tool to design a control system and convert Petri net to ladder diagram for PLC implementation becomes increasingly more important. Therefore, the objective of this paper is to design behaviorally optimal liveness-enforcing supervisor for automated manufacturing system and their ladder diagram for programmable logic controller (PLC) implementation. To do this, first, deadlock prevention method (elementary siphons control method) has been used to design a supervisor to prevent the deadlock in AMSs. Next, a token passing logic (TPL) technique has used to convert the resulted controlled model into ladder diagrams (LDs) for implementation. Finally, the presented methodology can be applied for multiproduct and sizes of AMSs and provided a more effective for PLC implementation.

Keywords: Deadlock prevention, automated manufacturing system, Petri net, siphon, programmable logic controller

1 Introduction

An automated manufacturing system (AMS) is a conglomeration of robots, machine tools, fixtures, and buffers. Different types of products enter the manufacturing system at separate points of time; the system can process these parts based on a specified sequence of operations and resource sharing. The sharing of resources leads to the occurrence of deadlock states in an AMS through its operation, in which the local or global system is incapacitated (Li et al. 2008b, Li et al. 2012b, Abdulaziz et al. 2015, Chen et al. 2015, Nasr et al. 2015, Kaid et al. 2019). Thus, there is a need for an effective deadlock-control algorithm to ensure that these deadlocks do not occur in an automated manufacturing system. Petri nets are a mathematical and a major graphical tool suitable for modeling, analyzing, and controlling deadlocks in AMSs. Petri nets are used to describe the characteristics and behavior of an AMS, such as synchronization, conflict, and sequences. In addition, they could be used to provide behavioral properties, for example, boundedness and liveness (Chen et al. 2011).

In the last three decades, there has been a deluge of deadlock-control algorithms based on Petri nets, which were developed for deadlock prevention in AMSs (Ezpeleta et al. 1995, Huang et al. 2001, Li and Zhou 2004, Uzam and Zhou 2004, Huang et al. 2006, Huang 2007, Li et al. 2007, Uzam and Zhou 2007, Li and Zhao 2008, Li and Zhou 2008, Li et al. 2008a, Chao 2010, Chen and Li 2011, Li et al. 2011, Li et al. 2012a, Chen et al. 2014a, Chen et al. 2014b, Chen et al. 2014c, Qin et al. 2015, Uzam et al. 2016). Most of the deadlock-control policies have been proposed via structural analysis (Chao 2009, Chao 2011) or reachability graph analysis (Ghaffari et al. 2003, Uzam 2004, Uzam and Zhou 2004, Nasr et al. 2015) of Petri nets. Deadlock-control algorithms (policies) based on reachability graph analysis can usually achieve a maximally permissive liveness-enforcing supervisor, but the former can lead to a suboptimally controlled system and the monitor number in a suboptimal supervisor depends on the Petri net size (Lautenbach 1987). The latter may encounter a problem of explosion state, since listing a portion or all of the reachable markings is necessary.
The control policies to prevent deadlocks in an AMS lead to a controlled system described by a Petri net. However, the results obtained in the supervisory control literature are mostly related to the theoretic studies as opposed to practical (implementation) studies. After designing a controller (supervisor), it is a need to have an automatic ways for the generation of control code from the controller to test the applicability of the deadlock prevention methods for real world systems and determining which methods are suitable for the systems that can definitely lead to the maximal permissiveness, structural complexity, and computational complexity. It is necessary to convert a controlled Petri net system representation into a programmable logic controller (PLC) implementation to evaluate the applicability of deadlock control methods to the execution of automation tasks. PLCs have appeared as a robust tool in the fulfillment of automation operations in industrial production systems. Ladder diagrams (LDs) are the most popular language used to program a PLC. The main problem with LDs is that programming is done heuristically. In simple manufacturing systems, it is not difficult to develop PLC programs with these methods. Nevertheless, when multiple systems are considered, the problem is magnified. Indeed, it is difficult to find ladder logic programs when the manufacturing system is single and has multiproduct types that are implemented using heuristic approaches (Venkatesh et al. 1994a, Venkatesh et al. 1994b). To overcome this problem, Petri nets can be used to provide a successful solution for the conceptual design, and the heuristic design is replaced by the transformation of Petri nets into LDs, which is introduced in (Satoh et al. 1992, Burns and Bidanda 1994, Jafari and Boucher 1994, Uzam and Jones 1998). In (Jones et al. 1996), a token-passing logic (TPL) technique has been introduced, which provides options to involve counters, flags, and timers. This technique is used in the transformation of an automation Petri Net (APN) into LDs. Moreover, the same technique has been used to handle the timed-transition Petri nets (Uzam et al. 1996), timed place Petri nets (Uzam and Jones 1996, Uzam et al. 1996), and colored Petri nets (Uzam et al. 1996).
This paper proposes a methodology based on Petri nets for deadlock prevention and generates PLC codes (ladder diagrams) for an AMS to elucidate the weaknesses or disadvantages of the existing methods in the literature. In addition, the contributions of this research are clearly emphasized.
The rest of the paper is structured as follows. Section 2 introduces Petri nets. The proposed methodology is described in Section 3. A real-world AMS case study is presented in Section 4. Finally, the conclusions and future research are given in Section 5.

2 Basics of Petri Nets

A place/transition net or Petri net N (Li et al. 2007, Chen et al. 2014a, Nasr et al. 2015) is a quadruple (P, T, F, W), where P is a non-empty and finite set of places, and T is a non-empty and finite set of transitions. Elements in $P \cup T$ are called nodes with $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$. P and T are graphically described by circles and bars, respectively. $F \subseteq (P \times T) \cup (T \times P)$ is the set of directed arcs (with arrows) that join the places with transitions, and vice versa. $W: (P \times T) \cup (T\ P \times T)\ \mathbb{N}$ is a mapping that allocates a weight to an arc, where $\mathbb{N} = \{0, 1, 2, ...\}$. N is called an ordinary or unweighted net if $\forall\ (p, t) \in F((t, p) \in F)$, $W(p, t) = 1$ $(W(t, p) = 1)$, denoted as $N = (P, T, F)$. N is called a weighted net if there is an arc between p and t with $W(p, t) > 1$ or $W(t, p) > 1$. If there is no arc between a place p and a transition t, we have $W(p, t) = W(t, p) = 0$.
Assume that a net $N = (P, T, F, W)$ and node $a \in P \cup T$, ${}^{\bullet}a = \{b \in P \cup T \mid (b, a) \in F\}$ is called the preset of node a, while $a^{\bullet} = \{b \in P \cup T \mid (a, b) \in F\}$ is called the post-set of node a. A marking M of N is a mapping $M: P \rightarrow \mathbb{N}$. (N, M_o) is a marked net or a net system, denoted as $PN = (P, T, F, W, M_o)$, where M_o is an initial marking. For a Petri net modelling an AMS, M_o indicates the various raw parts that are to be simultaneously processed in an AMS, and the initial capacity configuration of resources such as robots and machines. A transition $t \in T$ is enabled at marking M if $\forall p \in {}^{\bullet}t$, $M(p) \geq W(p, t)$, which is indicated as $M[t\rangle$. If a transition t fires, it withdraws $W(p, t)$ tokens from each place $p \in {}^{\bullet}t$, and stores $W(t, p)$ tokens in each place $p \in t^{\bullet}$. Thus it reaches a new marking M', indicated as $M[t\rangle M'$, where $M'(p) = M(p) - W(p, t) + W(t, p)$. A Petri net is pure or self-loop free if $\forall a, b \in P \cup T$, $W(b, a) = 0$ and $W(a, b) > 0$.

Incidence matrix $[N]$ is an integer matrix of a net N, which consists of $|T|$ columns and $|P|$ rows with $[N](p, t) = W(t, p) - W(p, t)$.
Suppose (N, M_0) is a net with $N = (P, T, F, W)$. It can be said that a transition $t \in T$ is live if for all $M \in R(N, M_0)$, $\exists M \in R(N, M)$, there exists a firing sequence such that $M[t\rangle M'$. A transition is in a deadlock state at M_o if $\nexists\, t \in T$, $M_0[t\rangle$ holds. M' is said to be reachable from M if there is a firable finite transition sequence $\delta = t_1t_2t_3 ... t_n$, and markings $M_1, M_2, M_3, ..., and\ M_{n-1}$ such that $M[t_1\rangle M1[t_2\rangle M_2[t_3\rangle M_2 ... M_{n-1}[t_n\rangle M1$ that is represented as $M[\delta\rangle M'$, satisfying the state equation $M' = M + [N]\, \vec{\delta}$, where $\vec{\delta} : T \to \mathbb{N}$ is a mapping from T to the number of appearances of t in δ, and called a firing count vector or a Parikh vector. The reachable set of markings from M in N is called the reachability set of a net (N, M), and is indicated as $R(N, M)$. Petri net N with an initial marking M_o is said to be k-bounded if $\forall M \in R(N, M_0)$, $M(p) \leq k\ (k \in \mathbb{N})$. Petri net N is said to be safe if all its places are safe, each place p does not have more than one token.
P-vectors (place vectors) and T-vectors (transition vectors) are column vectors. A P-vector $I: P \to Z$ catalogued by P is said to be a place invariant or P-invariant if $I \neq \mathbf{0}$ and $I^T. [N] = \mathbf{0}^T$, and a T-vector $J: T \to Z$ catalogued by T is said to be a transition invariant or T-invariant if $J \neq \mathbf{0}$ and $[N].J = \mathbf{0}$, where Z is the set of integers. When each element of I is non-negative, the place invariant I is called a place semiflow or P-semiflow. Assume that I is a P-invariant of a net with (N, M_o) and M is a reachable marking from the initial marking M_o. Then $I^T M = I^T M_o$. Let $\|I\| = \{p \mid I(p) \neq 0\}$ be the support of P-invariant I. The supports of P-invariant I are classified into three types: (1) $\|I\|^+$ is the positive support of P-invariant I with $\|I\|^+ = \{p | I(p) > 0\}$. (2) $\|I\|^-$ is the negative support of P-invariant I with $\|I\|^- = \{p \mid I(p) < 0\}$. (3) I is a minimal P-invariant if $\|I\|$ is not a superset of the support of any other one and its components are mutually prime. Let l_i be the coefficients of P-invariant I if $\forall\, p_i \in P$, $l_i = I(p_i)$. Since regular (ordinary and weighted) Petri nets do not handle both actuators and sensors, an extended Petri net has been developed to handle both actuators and sensors (Uzam and Jones 1998) and (Uzam et al. 1996), which is called an automation Petri net (APN). An APN is an octuple $(P, T, F, In, En, X, Q, M_o)$, where P, T, F, and M_o are explained above. In is an inhibitor arc, graphically represented by an arc with a small circle (not an arrow). An inhibitor arc connects an input place p to a transition t, and the transition t is enabled if the input place p has tokens that are less than the inhibitor arc weight $In(p, t)$. En is an enabling arc represented by an arc with an empty arrow. An enabling arc connects an input place p to a transition t. The transition t is enabled if the input place p has tokens whose number is at least equal to the enabling arc weight $En(p, t)$. $X = \{x_1, x_2, ..., x_m\}$ is the set of firing conditions associated with the transitions, which can be known as external events — for example, sensor readings. $Q = \{q_1, q_2, ..., q_n\}$ is the actions set, which can be allocated to the places. Q may represent more than one action in any place. In the APN, the movement of tokens between their places represents the behaviour of an APN, which is achieved via the firing of the transitions that are enabled.

3 Deadlock Prevention Method and Policy

This section presents a method that is motivated by (Li and Zhou 2004) and called an elementary siphons control method. The strict minimal siphons (SMS) in a Petri net are classified into elementary and dependent ones. In the sequel, $\prod$ is used to denote the set of strict minimal siphons, while $\prod_E$ and $\prod_D$ the sets of elementary and dependent (redundant) ones, respectively. Unless otherwise stated, we refer to a strict minimal one when mentioning a siphon.
Definition 3.1. (Li and Zhou 2004) Let $S \subseteq P$ be a siphon of N. P-vector λ_S is called the characteristic P-vector of S if $\forall p \in S$, $\lambda_S(p)=1$, otherwise $\lambda_S(p)=0$.
Definition 3.2. (Li and Zhou 2004) Let $N = (P, T, F)$ be a net with $|P| = m$, $|T|=n$ and we assume N has k SMS,S_1,S_2, …, and S_K, m, n, k $\in \mathbb{N}$. Let $\lambda_{Si}(\eta_{Si})$ be the characteristic $P(T)$ - vector of siphon S_i, i ∈ {1, 2, …n}. We define $[\lambda]_{kxm} = [\lambda_{S1}, \lambda_{S2}, \ldots, \lambda_{Sk}]^T$ and $[\eta]_{kxn}$=$[\lambda]_{kxm}.[N]_{mxn}$ is called the characteristic $P(T)$- vector matrix of the siphons of N, where $[N]_{mxn}$ is an incidence matrix.
It is easy to find elementary siphons in a Petri net system (N, M_0) given all siphons. To do this, first, we construct matrix $[\lambda]$ and then $[\eta]$, the number of elementary siphons in N is the rank of $[\eta]$.Then linearly independent vectors can be found in $[\eta]$. Finally, the siphons that correspond to these linearly independent vectors are the elementary siphons in the net system (N, M_0).
Theorem 3.1. Let N be an ordinary Petri net and S1-Sn be the siphons in N with respect to elementary siphons. Control place VS is added to N, the new net system is denoted as $(N1, M1)$ and the initial token of place control V_S is computed as M (V_S) =$M_0(S)$-ξ_S, $1 \leq \xi_S \leq M_0(S)$-1, where ξ_S is called the control depth variable of siphon S, which implies the least number of tokens that siphon can hold. Then S is invariant-controlled.
Theorem 3.2. Let (N, M_0) be a net system and S_0 be a strictly dependent siphon with respect to elementary siphons S_1 , S_2 , …, and S_n . If S_1, S_2, …, and S_n are invariant controlled by adding control places Vs_1, Vs_2, … and Vs_n, and $M_0(S_0) > \sum_{i=1}^{n} a_i .M_0(S_i) - \sum_{i=1}^{n} a_i .\xi_{Si}$ holds; then S_0 is controlled, where a_i is a constant. Based on the concept of

elementary siphons, the applied deadlock prevention algorithm developed by Li et al. (Li and Zhou 2005) is stated as follow:

Input: Petri net model (N, M_0)
Output: A controlled Petri net system (N_1, M_1).
Step 1: Find all strict minimal siphons of Petri net model N using INA software.
Step 2: T-vector matrix of the SMS [η].
Step 3: Find the elementary siphons of N. The others are the dependent siphons.
Step 4: For each elementary siphon S, add a control place Vs such that:

- ***The output and input arcs (weights are all ones) of Vs are connected to the source transitions that have paths leading to the sink transitions and connected from the stealing places of S respectively.***
- ***Compute the initial token of place control VS M (V_S) =$M_0(S)-\xi_S$, $1\leq \xi_S \leq M_0(S)-1$.***

Step 5: Repeat Step 4 until all elementary siphons are considered.
Step 6: Adjust ξ_i.such that each dependent siphon is controlled.

For instance, consider the system shown in Figure 1(a). Its Petri net model is illustrated in Figure 1(b). It consists of one robot R1 and two machines M1 and M2 that can hold and process one part at a time respectively, two loading and unloading buffers. Two parts types are considered in the system: PA and PB. The production sequence of the system is shown in Figure 1(c). There are 11 places and 8 transitions. The places have the following set partition: $P^0 = \{p_1, p_8\}$, $P_R = \{p_9, p_{10}, p_{11}\}$, and $P_A = \{p_2, \ldots, p_7\}$,where P^0, P_R, and P_A are input, resources, and operation places respectively. It has 8 minimal siphons, 3 of which are strict minimal siphons and 20 reachable markings. The three SMS are $S_1= \{p_4,p_7,p_9,p_{10},p_{11}\}$, $S_2= \{p_4,p_6,p_{10},p_{11}\}$, and $S_3= \{p_3,p_7,p_9,p_{10}\}$. The$[\lambda]$, $[N]$, and $[\eta]$ for the Petri net in Figure 1(b) are as follows. Obviously, the rank of $[\eta]$ is two since the first row η_{S1} can be linearly represented by the second and third rows. Therefore, S_1 is a dependent siphon and S_2 and S_3 are elementary siphons. For elementary siphon S_2 and S_3, due to Theorem 3.1, we add monitors V_{S2} and V_{S3} for them. V_{S2} has preset ${}^\bullet V_{s2}=\{ t_3,t_6\}$, postset $V_{s2}{}^\bullet=\{ t_2,t_5\}$, M($Vs_2$)=1, and ξ_{S2}=1. V_{S3} has preset ${}^\bullet V_{s3}=\{ t_2,t_7\}$, postset $V_{s3}{}^\bullet=\{ t_1,t_5\}$, $M(Vs_3)$=1, and ξ_{S3}=1. Figure 2(a) illustrates the controlled system of the Petri net in Figure 1(b) after adding monitors V_{S2} and V_{S3} by using the applied algorithm. Table 2 shows the required monitors using applied algorithm for Figure 1(b). The initial marking relationships between dependent siphon S_1 and elementary siphons S_2 and S_3 and the controllability of dependent siphons due to Theorem 3.2 are shown in Table 1. It can be seen that the dependent siphon S_1 is invariant controlled by adding monitors V_{S2} and V_{S3}.

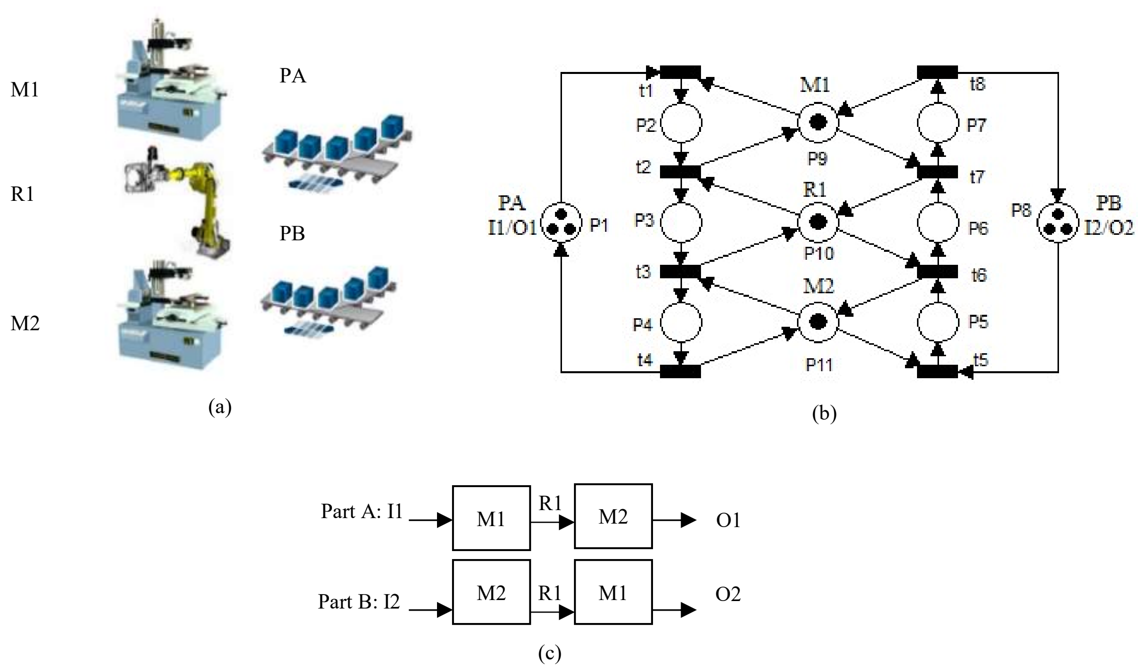


Figure 1: (a) An AMS example (b) Petri net model of an AMS (c) Production sequence

$$[\lambda] = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{pmatrix}$$

$$[\eta] = \begin{pmatrix} -1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 \\ 0 & -1 & 1 & 0 & -1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & -1 & 1 & 0 \end{pmatrix}$$

$$[N] = \begin{pmatrix} P\backslash T & t1 & t2 & t3 & t4 & t5 & t6 & t7 & t8 \\ p1 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ p2 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ p3 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ p4 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ p5 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ p6 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ p7 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ p8 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 \\ p9 & -1 & 1 & 0 & 0 & 0 & 0 & -1 & 1 \\ p10 & 0 & -1 & 1 & 0 & 0 & -1 & 1 & 0 \\ p11 & 0 & 0 & -1 & 1 & -1 & 1 & 0 & 0 \end{pmatrix}$$

Table 1: Required Monitors using applied algorithm

Siphon	$^{\bullet}V_{si}$	$V_{si}^{\bullet}$	$M_{oA}(V_{si})$
S_2	t_3,t_6	t_2,t_5	1
S_3	t_2,t_7	t_1,t_5	1

Table 2: Marking relationships between dependent and elementary siphons

Dependent	η relationship	Initial Marking Relationships, $M_0(S_0) > \sum_{i=1}^{n} a_i \cdot M_0(S_i) - \sum_{i=1}^{n} a_i \cdot \xi_{Si}$	Controlled
S_1	$\eta_1 = \eta_2 + \eta_3$	$M_0(S_1) > (M_0(S_2) + M_0(S_3)) - (\xi_{S2} + \xi_{S3})$ 3>(2+2)-(1+1), 3>2	Yes

4 The Proposed Methodology

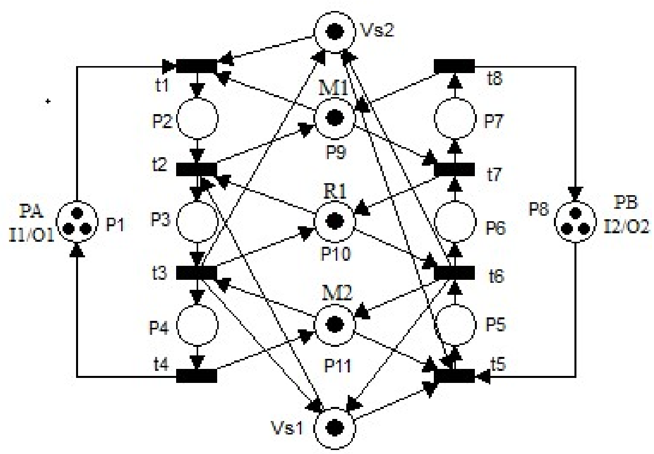
This section presents the proposed methodology that used to design behaviorally optimal liveness-enforcing supervisor for automated manufacturing system and their ladder diagram for programmable logic controller (PLC) implementation. The proposed methodology is stated as follow:

Step 1: build the Petri net model of the uncontrolled system (PN) and obtain the controlled Petri net model (CPN). In this step, an elementary siphons control method is used to design a deadlock control supervisor, which is explained in detail in section 3.

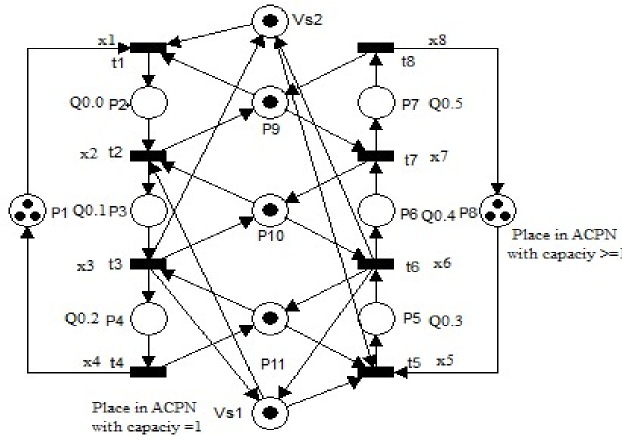
Step 2: Convert the controlled Petri net model (CPN) into the automation controlled Petri net model (ACPN). In this step, the CPN is converted into ACPN by (Uzam and Jones 1998) to determine the firing conditions X, Actions Q, and the capacity of the places. Figure 2(b) displays the automation controlled Petri net model of numerical example.

Step 3: Convert the automation controlled Petri net model (ACPN) into controlled token passing logic model (CTPL). In this step, a token-passing logic technique that proposed by (Jones et al. 1996) is used to facilitate the direct transformation of an automation Petri net into a control logic, which can be achieved with ladder diagram program (Uzam and Jones 1998). Each place in ACPN corresponds to a place in CTPL. The simulated movement of tokens at each place in the CTPL is achieved by deploying memory words (16 bits) at each one; each place has at least an associated memory word in TPL, where the capacity of each place is at least one. If the stored value of a memory word of a place in the TPL is at least one and the firing condition x of a transition that associated with that place becomes enabled, then the memory word at the input and output places might be decreased and increased, respectively. Note that the flags and counters can be used instead of memory bits and memory words, respectively (Uzam and Jones 1998). Figure 2(c) illustrates the equivalent CTPL for the ACPN of numerical example.

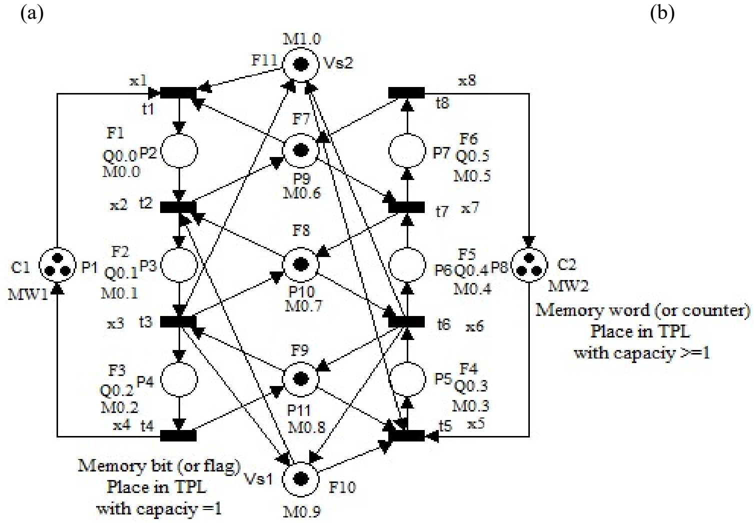
Step 4: Convert the controlled token passing logic model into ladder diagrams (LDs). In this step, the conversion of the CTPL model to ladder diagrams is proposed in (Uzam and Jones 1998), the controlled token passing logic model converted directly into ladder diagrams. Note that the conversion the TPL for numerical example into PLC code will not be handled and explained in the next manufacturing case study.



(a)



(b)

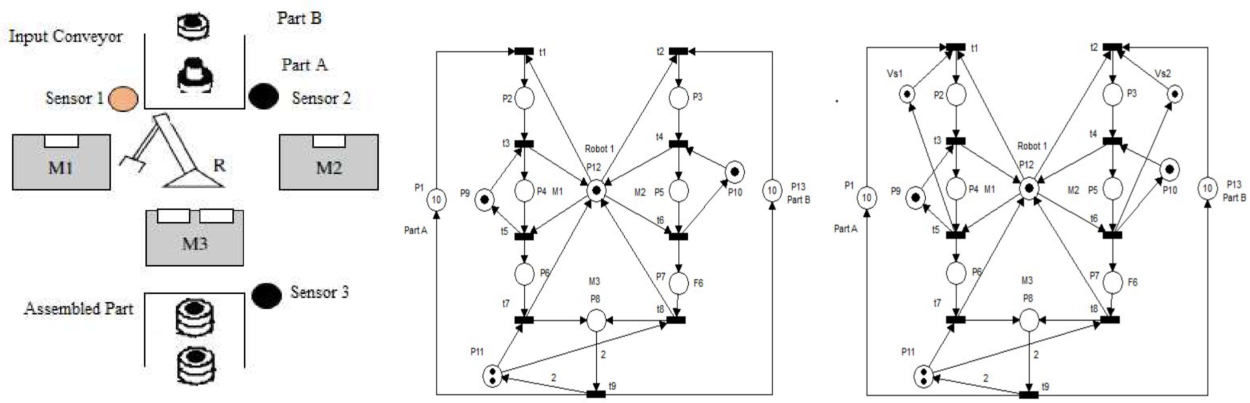


(c)

Figure 2: (a) A controlled system (b) ACPN for the controlled system (c) The equivalent CTPL

5 Case Study

A flexible manufacturing system (FMS) shown in Figure 3(a) is considered. It consists of three machines M1-M3, M1 and M2 can process one part at a time, M3 can assemble two parts at a time, input and output conveyors, and one robot that can hold one part at a time. Two types of parts are considered in the system: PA and PB. Parts A and B should be produced at machines M1 and M2 respectively, and subsequent assembled in machine M3 to obtain a final product that leaves the manufacturing cell. In this case, study a robot, working in mutual exclusion, feeds M1 and M2 from input conveyor, and moves parts A and B from M1 and M2 to M3. The system has two problem, which are identification and recognition of two input parts and deadlock in the system. The implementation of the proposed methodology is shown in the following steps.



(a) (b) (c)

Figure 3: (a) Flexible manufacturing system (b) The equivalent Petri net model

Step 1: Controlled Petri net model (CPN) for FMS

The Petri net model of FMS shown in Figure 3(b). The places have the following set partition: $P^0 = \{p_1, p_{13}\}$, $P_R = \{p_9, ..., p_{12}\}$, and $P_A = \{p_2, ..., p_8\}$. It has three SMS, 1 and 2 of which are dependent siphon and elementary siphons, respectively. Moreover, it has 872 reachable markings. The required monitors that obtained by the applied algorithm is shown in Table 3. The CPN is shown in Figure 3(c).

Table 3: Required Monitors using applied algorithm for FMS

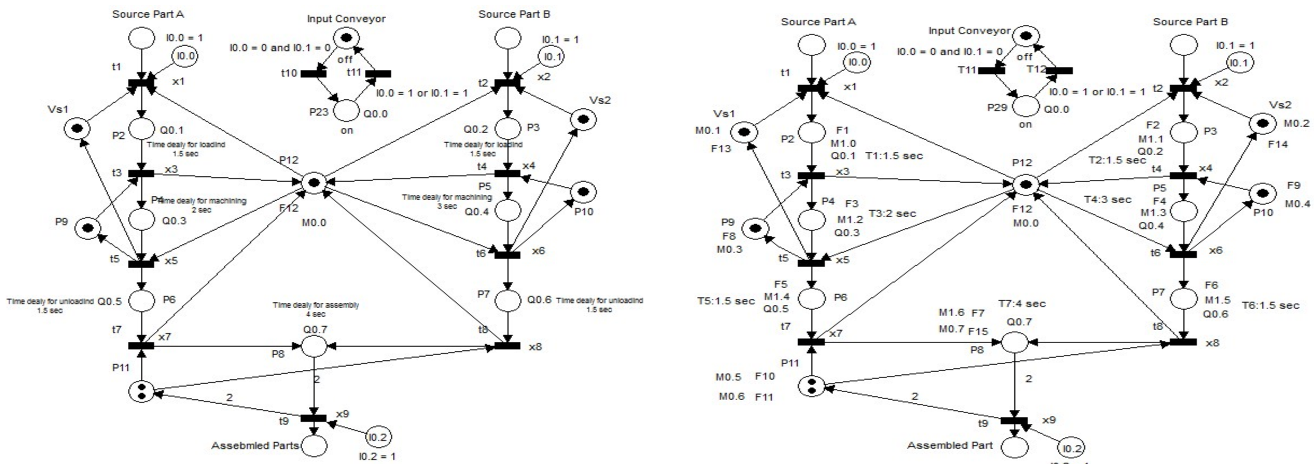
Siphon	$^\bullet V_{si}$	$V_{si}^\bullet$	$M_{oA}(V_{si})$
S_1	t_5	t_1	1
S_2	t_6	t_2	1

Step 2: ACPN Model for FMS

In this step, the CPN has identification and recognition of two input parts and final assembled part. To solve this problem three sensors are added on input and output conveyors. For input conveyor, sensor 1 (proximity sensor) and sensor 2 (an infra-red reflective sensor) are used to recognize Part A and Part B, respectively. Moreover, sensor 3 is added to the end of model to detect the final assembled part. Now a designed ACPN model for the controlled system using applied algorithm is shown in Figure 4(a). In the ACPN model, the firing conditions (Xi) are assigned to the transitions, and level actions (Qx.x) are assigned to the operation places. Moreover, delay timer is associated with timed for each operation place to represent the time delays.

Step 3: CTPL for FMS

The CTPL is obtained by applying the TPL concept to the ACPN model. Where memory bits (Mx.x) are assigned to the places, whose capacity is one. Note that an assembly machine state has two tokens, thus we have assigned two memory bits. An on delay timer is associated with timed places, to represent the time delays. Moreover, output bits, Q0.0, Q0. One, Q0.2, Q0.3, Q0.4, Q0.5, Q0.6, and Q0.7, are assigned to the control places to represent actions at places. Sensor readings are realized by input registers, I0.0, I0.1, and I0.2. Table 4 shows the PLC inputs and outputs for the system. . Now a designed CTPL model for the ACPN model is shown in Figure 4(b).



(a) (b)

Figure 4: (a) ACPN for the FMS (b) The equivalent CTPL

Table 4: PLC inputs and outputs

Parameter	Definition	Parameter	Definition
I0.0	Detects a Part A in input conveyor	Q0.3	Operation of M1
I0.1	Detects a Part B in input conveyor	Q0.4	Operation of M2
I0.2	Detects a assembled part after M3	Q0.5	Unloading Part A by Robot
Q0.0	Input conveyor motor	Q0.6	Unloading Part B by Robot
Q0.1	Loading Part A by Robot	Q0.7	Operation of M3
Q0.2	Loading Part B by Robot		

Step 4: LD for the TPL

The CTPL is converted directly into LD code for implementation. The obtained LD code is illustrated in Figure 5. The LD code has been structured in such a way that rungs 1, 2, 3, 4, and 5 denote the off and on state of resources and control places of the system, which are robot, control place VS1, control place VS2, M1, and M2, respectively. Moreover, rungs 6, 7, and 8 imply the off and on state of M3. Rungs 9, 10, 11, 12, 13, 14, and 15 represent the memories states of resources operations, which are loading part A to M1 via Robot, loading part B to M2 via Robot, machining part A in M1, machining part B in M2, move part A to M3 via Robot, move part B to M3 via Robot, and assembling parts A and B in M3, respectively. In addition, rungs 16, 17, 18, 19, 20, 21, and 22 denote the actions and time delays of resources operations, which are loading part A to M1 via Robot, loading part B to M2 via Robot, machining part A in M1, machining part B in M2, move part A to M3 via Robot, move part B to M3 via Robot, and assembling parts A and B in M3, respectively. Finally, rung 23 implies the input conveyor operation.

6 Conclusion

In this paper, a methodology has been described by considering a manufacturing system. First, deadlock prevention method (elementary siphons control method) has been used to design supervisor to prevent the deadlock in manufacturing system. Next, an ACPN model has been designed for the resulted controlled model. Then, the APN model has been converted into a token passing logic (CTPL), so that the specifications were met. Finally, the ladder diagram (LD) for implementation on a PLC has been obtained by using a direct converting from the CTPL into LD. The methodology well suited to multiproduct systems and provides a more effective for PLC implementation. The verification of this methodology has not been addressed, thus it is an important issue to be considered in the future work. Moreover, our future work involves applying a methodology for different deadlock prevention policies. Different and complex automated manufacturing systems are required.

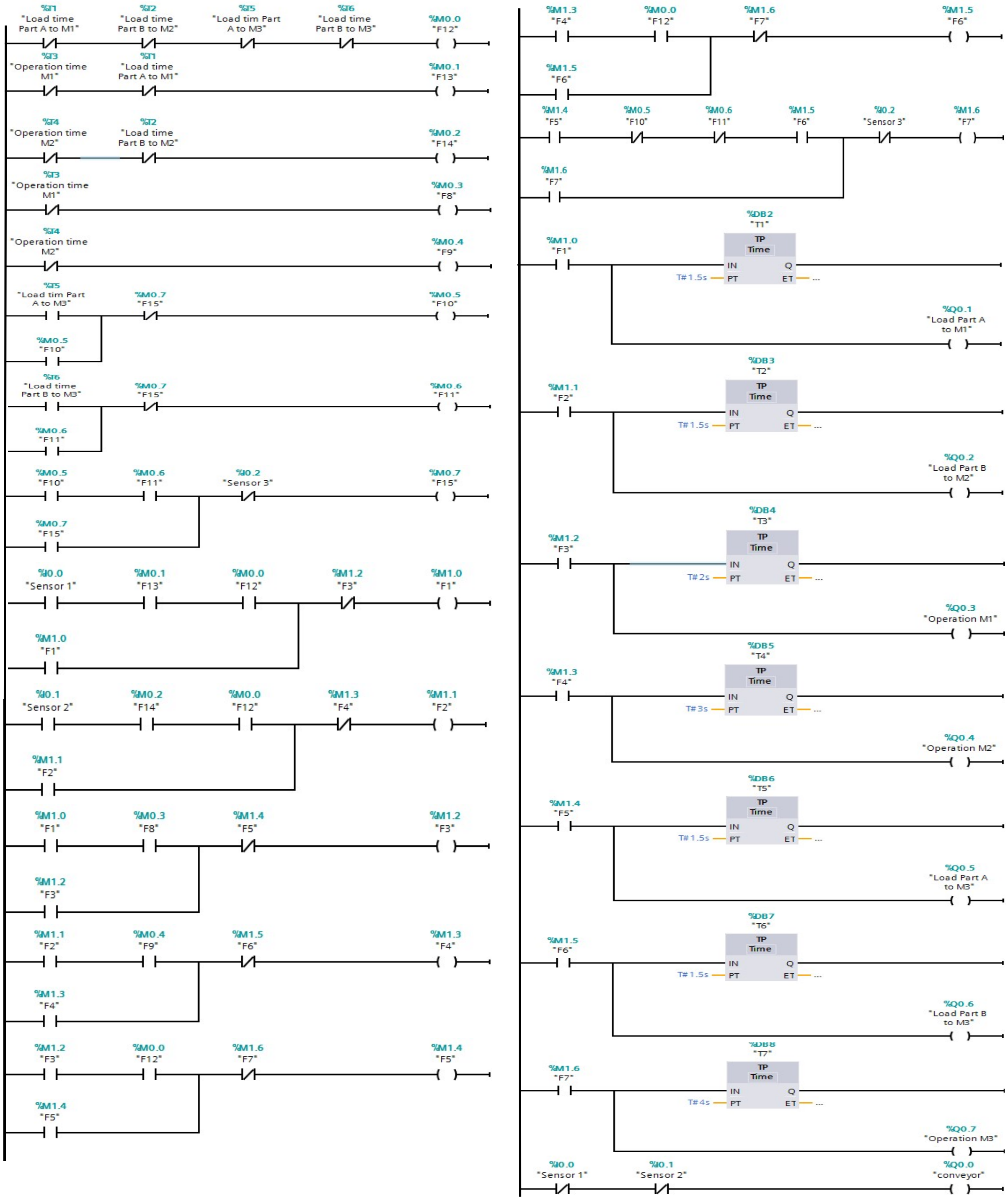


Figure 5: LD code for the CTPL

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