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Comparison of Two Deadlock Prevention Methods for Different-size Flexible Manufacturing Systems

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Abstract- **The competition for limited resources can produce deadlocks in flexible manufacturing systems (FMS). Petri nets are an effective way to model, analyze, and control deadlocks in FMS. Our previous work proposes elementary siphons as an important concept in investigating the deadlock problems in Petri nets. This paper presents an elementary siphon-based deadlock prevention method. It then performs the analysis of this new policy and a well-established deadlock prevention policy based on strict minimal siphons. Both methods are used to solve the deadlock control problems for a number of FMS with different scales. This paper concludes that the new policy can always lead to structurally simple liveness-enforcing net supervisors than the other method.**

***Index Terms*—Petri net, flexible manufacturing system, Deadlock prevention, elementary siphon.**

1. INTRODUCTION

Manufacturers must adapt to changes in the production environment as well as in the market in order to achieve and maintain global competitiveness. Flexible manufacturing systems (FMS), when designed and operated effectively, can be of assistance to manufacturers in attaining this goal. In an FMS, different types of raw parts enter the system at discrete points of time and are processed concurrently, sharing a limited number of resources such as machine tools, AGVs, robots, buffers, and fixtures. Every raw part follows a pre-established production sequence through the set of system resources.

These production sequences are concurrently executed and therefore they have to compete for the set of shared resources. This competition for shared resources can cause deadlocks, a highly undesirable situation, where each of a set of two or more jobs keeps waiting indefinitely for other jobs in the set to release resources. Deadlocks and related blocking phenomena often cause unnecessary cost, e.g., long downtime and low use of some critical and expensive resources, and may lead to catastrophic results in highly automated manufacturing systems, e.g., semiconductor production systems. Hence, it becomes a requirement to develop an effective FMS control policy to make sure that deadlocks will never occur in the system. This paper focuses on the deadlock problems in such FMS.

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Digraphs, automata, and Petri nets are major mathematical tools to characterize, analyze, and control deadlocks in various resource allocation systems including FMS. The graph-theoretic approaches are a simple and intuitive tool, which are suitable for describing the interaction between jobs and resources even in complex resource allocation systems and permit the derivation of detection and avoidance strategies [6, 11].

Finite state automata, as an important and efficient formal framework to describe the behavior of FMS, are adopted to establish deadlock control policies in [18, 23, 24]. Many researchers use Petri nets [21] as a formalism to describe the behavior of FMS [32] and develop appropriate deadlock resolution methods. The major strategies using Petri net techniques to cope with deadlocks in FMS are deadlock detection and recovery [29], deadlock avoidance [28, 9, 13, 2, 10], and deadlock prevention. In FMS context, deadlock prevention is usually achieved either by effective system design [32, 31, 16] or by using an off-line mechanism to control the requests for resources to ensure that deadlocks never occur. Monitors or control places and related arcs are often used to achieve such purposes [3, 8, 15, 1, 14, 25, 4, 30, 22, 19, 26, 27]. This implies that both a plant model and its supervisor are in a Petri net formalism. In particular, for a class of Petri nets, S^3PR, Ezpeleta *et al.* [8] proposed a prevention control policy by adding monitors (control places) to a plant Petri net model such that the final supervisor is live. The monitors are used to prevent the presence of unmarked siphons that are direct cause of deadlocks in such a Petri net. However, all output arcs of the monitors are added to the source transitions of the plant net model. Since the source transitions in an S^3PR denote the entry points of the processing of raw parts, this policy is conservative. Moreover, it needs complete siphon enumeration whose computation is very time-consuming when dealing with a large-size Petri net model.

Usually, each possibly emptiable minimal siphon requires a monitor to be added to prevent itself from being emptied. Unfortunately the number of such siphons in a net grows quickly and in the worst case grows exponentially with respect to the size of the net [17]. Hence, the shortcoming of the existing methods is that they need to introduce too many additional monitors when the number of such siphons is large, leading to a much more structurally complex Petri net supervisor than the plant net model. To avoid complete siphon enumeration, Huang *et al.* (2001) proposed a two-stage deadlock prevention policy.

At the first stage, a maximal siphon is obtained by mixed integer programming (MIP). Then a monitor is added for each minimal siphon derived from the maximal one. Control-induced siphons can possibly be produced due to the addition of monitors. At the second stage, monitors are added to prevent control-induced siphons (if there exist such ones) controlled without generating new problematic siphons. This policy can usually lead to a more permissive liveness-enforcing Petri net supervisor for S^3PR than that proposed in [8].

In this particular research, we develop an elementary siphon deadlock control policy. Also, we compare the structural complexity of the liveness-enforcing supervisors with an established policy in the literature.

The rest of the paper is organized as follows. Section 2 reviews the basics of Petri nets. The concept of elementary and dependent siphons is given in Section 3. The deadlock control policy based on elementary siphons is developed in Section 4. And Section 5 shows the experimental results through a few different-scale FMS examples. Section 6 concludes this paper.

2. BASICS OF PETRI NETS

Petri nets are a graphical and mathematical modeling tool applicable to many systems. It is a promising tool for describing and studying information processing systems that are characterized as being concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic. The main definitions related to Petri net models are introduced in a very compact way. For a complete study of this subject, the reader is referred to [2], [9], [10].

A Petri net is a 3-tuple N=(P, T, F) where P and T are finite, nonempty, and disjoint sets. P is the set of places and T is the set of transitions. $F\subseteq(P\times T)\cup(T\times P)$ is called the flow relation. The preset of a node $x\in P\cup T$ is defined as ${}^\bullet x=\{y\in P\cup T|(y, x)\in F\}$. The postset of a node $x\in P\cup T$ is defined as $x^\bullet=\{y\in P\cup T|(x, y)\in F\}$. The preset (postset) of a set is defined as the union of the presets (postsets) of their elements. A marking of N is a mapping $M:P\rightarrow IN$, where $IN=\{0, 1, 2, \cdots\}$. (N, M) is called a net system or a marked net. M[t> means that transition t can be fired under M. The set of all markings reachable from a marking M_0, in symbols R (N, M_0), is the smallest set in which $M_0\in R(N, M_0)$ and $M'\in R(N, M_0)$ if both $M\in R(N, M_0)$ and $M_0[\sigma>M'$ hold, where σ is a friable transition sequence. Let (N, M_0) be a net system and N= (P, T, F). A transition $t\in T$ is live under M_0 if and only if $\forall M\in R(N, M_0)$, $\exists M'\in R(N, M)$, M'[t> holds. N is dead under M_0 if and only if $\neg\exists t\in T$: M_0[t> holds. (N, M_0) is deadlock-free if and only if $\forall M\in R$ (N, M_0), $\exists t\in T$, M[t> holds. (N, M_0) is live if and only if $\forall t\in T$, t is live under M_0. (N, M_0) is bounded if and only if $\exists k\in IN\backslash\{0\}$, $\forall M\in R(N, M_0)$, $\forall p\in P$, $M(p)\leq k$ holds. A P-vector is a column vector I: $P\rightarrow Z$ indexed by P and a T-vector is a column vector J: $T\rightarrow Z$ indexed by T, where Z is the set of integers. The incidence matrix of N is a matrix [N]: $P\times T\rightarrow Z$ indexed by P and T such that [N](p, t)=−1 if $p\in{}^\bullet t\backslash t^\bullet$; [N](p, t)=1 if $p\in t^\bullet\backslash{}^\bullet t$; and otherwise [N](p, t)=0 for all $p\in P$ and $t\in T$. We denote column vectors where every entry equals 0(1) by **0**(**1**). I^T and $[N]^T$ are the transposed versions of a vector I and a matrix [N], respectively. I is a P-invariant if and only if $I\neq 0$ and $I^T\bullet[N]=\mathbf{0}^T$ hold. J is a T-invariant iff $J\neq 0$ and $[N]\bullet J=\mathbf{0}$ hold. $||I||=\{p\in P|I(p)\neq 0\}$ ($||J||=\{t\in T|J(t)\neq 0\}$) is called the support of I (J). A nonempty set $S\subseteq P$ is a siphon if and only if ${}^\bullet S\subseteq S^\bullet$ holds. $S\subseteq P$ is a trap iff $S^\bullet\subseteq{}^\bullet S$ holds. A siphon is minimal iff there is no siphon contained in S as a proper subset. M(p) indicates the number of tokens in p under M. p is marked by M iff M (p)>0. A subset $S\subseteq P$ is marked by M iff at least one place in S is marked by M. The sum of tokens on all places in S is denoted by M(S), where $M(S)=\Sigma_{p\in D}M(p)$. A minimal siphon that does not contain a marked trap is called a strict minimal siphon.

Let (N, M_0) be a net system with N=(P, T, F), let I be a P-invariant, and $S\subseteq P$ be a siphon of N, Siphon S is controlled by P-invariant I under M_0 iff $I^T\bullet M_0>0$ and $\{p\in P|I(p)>0\}\subseteq S$. Such a siphon is also called an invariant-controlled siphon [6]. The following properties are known: (1) If I is a P-invariant of N then $\forall M\in R(N, M_0)$, $I^T\bullet M=I^T\bullet M_0$. (2) Let $S\subseteq P$ be a siphon of N. If S is controlled by a P-invariant I under M_0, S cannot be emptied, i.e., $\forall M\in R(N, M_0)$, S is marked under M. (3) If (N, M_0) is dead, the set of all unmarked places forms a siphon. If no minimal siphon in N can be emptied, (N, M_0) is deadlock free.

3. ELEMENTARY SIPHONS

We distinguish the strict minimal siphons (SMS) in a Petri net by elementary and dependent ones. In the sequel, Π is used to denote the set of strict minimal siphons, while Π_E and Π_D the sets of elementary and dependent ones, respectively. Unless otherwise stated, we refer to a strict minimal one when mentioning a siphon.

Definition 1: Let $S\subseteq P$ be a siphon of N. P-vector λ_S is called the characteristic P-vector of S iff $\forall p\in S$, $\lambda_S(p)=1$, otherwise $\lambda_S(p)=0$.

Definition 2: Let $S\subseteq P$ be a siphon of N. η_S is called the characteristic T-vector of S if $\eta_S^T=\lambda_S^T\bullet[N]$ holds.

Definition 3: Let S_1-S_n be the siphons in net N. T-Vectors η_1, η_2, …, and η_n form a vector space [η]. The base of the vector space is denoted by $\eta_B=\{\eta_{B1}, \eta_{B2}, \ldots, \eta_{Bk}\}$, where k is the rank of the vector space. Then $\{S_{B1}, S_{B2}, \ldots$, and $S_{Bk}\}$ is called a set of elementary siphons in net N.

Definition 4: Let $S\in\Pi\backslash\Pi_E$ be a siphon in a net N and S_1, S_2, …,$S_n\in\Pi_E$. S is strongly dependent on S_1-S_n if $\eta_S=\sum_{i=1}^{n}a_i\bullet\eta_i$ holds, where $a_i>0$.

Definition 5: Let $S\in\Pi\backslash\Pi_E$ be a siphon of net N and S_1, S_2, … ,S_n, S_{n+1}, S_{n+2}, …, and $S_{n+m}\in\Pi_E$ ($n\geq 1$, $m\geq 1$). S is weakly dependent on elementary siphons S_1-S_{n+m} if η_i

$=\sum_{i=1}^{n} a_i \bullet \eta_{S_i} - \sum_{j=n+1}^{n+m} a_j \bullet \eta_{S_j}$ holds, where $\forall i, j \in \{1, 2, \ldots, n+m\}$, $a_i>0$, $a_j>0$.

If S is dependent on S_1-S_k, we say that S_1-S_k are the elementary siphons of S. The following results are from our previous work [19].

Theorem 1: Let N_0 be a marked net and $S=\{p_{i1}, p_{i2}, \cdots, p_{in}\}$ be a siphon in N_0. Control place V_S is added to N_0, the new net system is denoted as (N_1, M_1), such that: 1) $I_l=(\cdots, 1p_{i1}, 1p_{i2}, \cdots, 1p_{in}, \cdots, -1v_s, \cdots)^T$ is a P-invariant of N_1, 2) $M_1(V_S)=M_0(S)-\xi_s$, where $1\le\xi_s\le M_0(S)-1$, and 3) $\forall p\in P_0$, $M_1(p)=M_0(p)$, where P_0 is the set of places of N_0. Then S is invariant-controlled.

ξ_s is called the control depth variable of siphon S. In the sequel, the initial net system is denoted as (N, M_0) and the net system with additional places is denoted by (N_1, M_1). We assume that in a plant net model (N, M_0), $\forall S\in\Pi$, $\forall M \in R(N,M_0)$, $M_0(S)\ge M(S)$. This is true for manufacturing-oriented Petri net subclasses in the literature including S^3PR. The plant net model with such a property is called a well-initially-marked net. Next results show the conditions under which a dependent siphon is controlled when its elementary siphons are invariant-controlled.

Theorem 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 V_{s1}, V_{s2}, … and V_{sn}, and $M_0(S_0)>\Sigma^n_{i=1}a_i\cdot M_0(S_i)-\Sigma^n_{i=1}a_i\cdot\xi_{si}$ holds, then S_0 is invariant controlled.

Theorem 3: Let (N, M_0) be a well-initially-marked net system and S_0 be a generally dependent siphon with respect to elementary siphons S_1, S_2, ···, S_n, S_{n+1}, S_{n+2}, ···, and S_{n+m} which means $\eta s_0=\Sigma^n_{i=1}a_i\cdot\eta s_i-\Sigma^{n+m}_{j=n+1}a_i\cdot\eta s_j$. If S_1, S_2, ···, S_n, S_{n+1}, S_{n+2}, ···, and S_{n+m} are invariant-controlled by adding control places Vs_1, Vs_2, ··· Vs_{n+m}, ··· and $M_0(S_0)>\Sigma^n_{i=1}a_i\cdot M_0(S_i)-\Sigma^n_{i=1}a_i\cdot\xi_{si}$, where $1\le\xi_{si}\le M_0(S_i)-1$, S_0 is controlled.

Theorem 4: Let N=(P, T, F) be a net and ω the number of elementary siphons of N. We have $\omega\le\min(|P|, |T|)$.

This indicates that the number of elementary siphons is bounded by the smaller of place count and transition count in a Petri net. From Theorems 3 and 4, a dependent siphon can be implicitly controlled under some conditions related to its elementary siphons. As a result, we are motivated to develop the elementary siphons based deadlock prevention policy by adding monitors for elementary siphons only. The controllability of dependent siphons can be ensured by properly setting the control depth variables of related elementary ones.

4. ELEMENTARY SIPHON BASED POLICY

In this section, before introducing the proposed policy that is based on elementary siphons, we first review Ezpeleta's Siphon Control Policy.

Algorithm 1--Ezpeleta's Policy
Given an S^3PR:
Step 1: Find all strict minimal siphons of a given S^3PR N.
Step 2: For each siphon S, add a control place V_s such that:
a) The output arcs (weights are all ones) of V_s are connected to the source transitions that have paths leading to the sink transitions of S.
b) The input arcs (weights are all ones) of V_s are connected to the transitions related to the stealing places of S.
c) $M_0(V_s)=M_0(S)-1$.
Step 3: Repeat Step 2 until all such siphons are considered.

Algorithm 2--Elementary Siphon Based Policy
Given an S^3PR:
Step 1: Find all strict minimal siphons of a given S^3PR N.
Step 2: Find the elementary siphons of N. The others are the dependent siphons (S_R).
Step 3: For each elementary siphon S, add a control place V_s such that:
a) The output arcs (weights are all ones) of V_s are connected to the source transitions that have paths leading to the sink transitions of S.
b) The input arcs (weights are all ones) of V_s are connected from the stealing places of S.
c) $1\le\xi_s\le M_0(S)-1$, $M_0(V_s)=M_0(S)-\xi$.
Step 4: Repeat Step 3 until all elementary siphons are considered.
Step 5: Adjust ξ_i such that each dependent siphon (S_R) is controlled.

Theorem 5: Let (N, M_0) be a marked S^3PR, $N=(P_0\cup P \cup P_R, T, F)$. By algorithm 1 or 2, m control places V_{S1}, V_{S2}, …, V_{Sm} are added to N. The new net system is denoted by (N', M_0'). The addition of these monitors cannot generate emptiable control-induced siphons.

Proof: Suppose that $V=\{V_{S1},V_{S2}, \ldots, V_{Sm}\}$ is added to N such that elementary siphons S_1, S_2, …, and S_m are invariant-controlled. By contradiction, the addition generates a new emptiable strict minimal siphon S. The following steps can clarify that is not true.

1. We claim that S contains at least one additional control place. This is so since if S contains no control place, taking the form of $S=\{p_1, p_2, \ldots, p_n\}$, it is a siphon in N. Thus, S is not a new one.

2. We claim that there is no new strict minimal siphon in N'. By contradiction, we assume $S=\{V_{Si}, r_1, r_2, \ldots, r_i, p_1, p_2, \ldots, p_n\}$ is a new strict minimal siphon, i.e. ${}^\bullet S\subset S^\bullet$. Let t_r be a source transition, and $p_0\in P^0$. Without the loss of generality, we select V_{Si} form the set of V freely. We can get $t_r^\bullet=\{p_r\}$, $p_r\in P$, $r\in P_R$, and $V_{Si}^\bullet=t_r$, as shown in Fig. 1.

2.1 S contains p_0 or r, where $t_r\in p_0^\bullet\cup r^\bullet$. Removing V_{Si} from S, we call the set of remaining elements S_0. That is to say, ${}^\bullet V_{Si}$ and $V_{Si}^\bullet$ are moved from ${}^\bullet S$ and $S^\bullet$, respectively. We can get easily ${}^\bullet S_0\subset{}^\bullet S$. Considering $V_{Si}^\bullet=t_r$ and $t_r\in$

$S_0^\bullet$, we have $^\bullet S_0 \subset {}^\bullet S \subset S^\bullet \subset S_0^\bullet$. Thus, S_0 is a siphon, which contradicts the minimality of S.

2.2 By contradiction. If S contains no p_0 or r, where $t_r \in p_0^\bullet \cup r^\bullet$, S is not a strict minimal siphon. We discuss it in following two cases.

2.2.1 If S does not contain p_r, $p_r \in t_r^\bullet$, then S is not a minimal siphon. Since $t_r \notin p_0^\bullet \cup r^\bullet$, as in 2.1, removing V_{Si} from S, we can conclude $^\bullet S_0 \subset {}^\bullet S$, and $S^\bullet = S_0^\bullet$. Therefore, $^\bullet S_0 \subset {}^\bullet S \subset S^\bullet = S_0^\bullet$ holds. It means S_0 is a siphon, which contradicts the minimality of S.

2.2.2 S is the support of a P-invariant if S contains p_r, where $\{p_r\} = t_r^\bullet$.

To prove this result, we have two steps. First, S is the support of a P-invariant if there is no any r, $r \in P_R$, in S. We construct S from $S = \{V_{Si}\}$. Since $t_l \in {}^\bullet V_{Si}$, a place p_1 is in S, where $p_1^\bullet$ has only t_l. Since $^\bullet p_1$ has only t_2 and $t_2 \in S^\bullet$, thus p_2 is in S, where $p_2^\bullet$ has only t_2. This reasoning is applied continuously. We can finally have $\{p | p \in P, p \in H(V_{Si})\} \subseteq S$. That is to say, S contains $V_{Si} \cup H(V_{Si})$, and in fact it contains $V_{Si} \cup H(V_{Si})$ only. This means S is the support of a P-invariant and a minimal siphon. Next, we prove there is no r, $r \in P_R$, indeed in S. By contradiction, we assume S contains resource places, and all resource places form a set $R = \{r_1, r_2, \ldots, r_i\}$. $\exists r_j \in R$, $t_j \in r_j^\bullet$, where t_r and t_j are satisfied with following conditions:

(1) t_j and t_r are in a process α; (2) $T = \{t_1, t_2, \ldots, t_m\}$, where $T \subseteq R^\bullet$.

All elements in T are in the process α. Of course, we have $t_r, t_j \in T$. Of all elements in T, t_j is the earliest fired transition after t_r fired in this process, as shown in Fig. 1.

We define a set $P_1 = \{p_{j+1}, p_{j+2}, \ldots, p_{r-1}, p_r\}$, as shown in Fig. 1. Above conditions mean that $\forall p \in P_1$ and $r \in R$, we always have $p \notin H(r)$. Furthermore, $\forall r \in R$, $t_r \notin H(r)$. Hence, if we want to have p_r in S, such a transition t_j can be always found in this process. Extremely, P_1 contains place p_r only, and in this case, $p_{j+1} = p_r$ and $t_j = t_{r-1}$ hold.

From the above discussion, we get the following results: $^\bullet p_r = V_S^\bullet$ contains only t_r, $p_r^\bullet = {}^\bullet p_{r-1}$, $p_{r-1}^\bullet = {}^\bullet p_{r-2}$, …, $^\bullet p_{j+1} = p_{j+2}^\bullet$, and $p_{j+1}^\bullet$ contains t_j only, where $t_j \in r_j^\bullet$. That is to say, $^\bullet P_1 = \{t_r, {}^\bullet p_{r-1}, {}^\bullet p_{r-2}, \ldots, {}^\bullet p_{j+1}, {}^\bullet p_{j+1}\}$, and $P_1^\bullet = \{p_r^\bullet, p_{r-1}^\bullet, \ldots, p_{j+2}^\bullet, t_j\}$. Removing P_1 from S, we get S_P. Clearly, we have $^\bullet S_p \cap {}^\bullet P_1 = \emptyset$, $S_p^\bullet \cap P_1^\bullet = \{t_j\}$, and $^\bullet S \subset S^\bullet$. Therefore, we have $^\bullet S_p \subset S_p^\bullet$, i.e. S_p is a siphon as well. However, this contradicts the minimality of S. Therefore, it is impossible that S contains $r \in P_R$.

From the above discussions, we only mention one of processes, to which $H(V_{Si})$ belongs. Similarly, we can get the same results in other processes. Therefore, taking the output arcs of any control place V_{Si} to the source transitions cannot generate a strict minimal siphon.

3. Taking output arcs of any control place V_S to the source transitions, we have no new emptiable strict minimal siphon in N'. We can conclude that taking output arcs of control places to the source transitions cannot generate new emptiable minimal siphon in N'. ♦

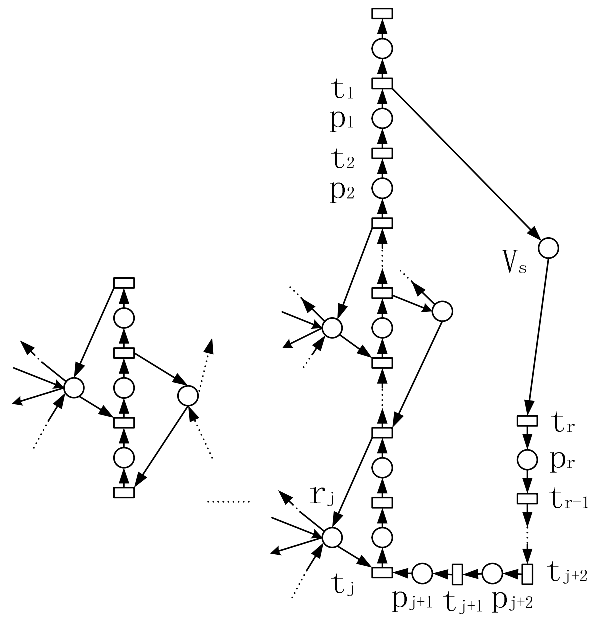

Fig. 1. A partial structure of ES^3PR net.

Theorem 6: Let (N, M_0) be a marked S^3PR, $N = (P_0 \cup P \cup P_R, T, F)$. By Theorem 1, m control places $V_{S1}, V_{S2}, \ldots$, and V_{Sm} are added to N. The new net system is denoted by (N', M_0'). The addition of these monitors cannot generate emptiable control-induced siphons.

Proof: This is trivial since Algorithms 1 and 2 are the special cases of Theorem 1. ♦

Theorem 7: Given an S^3PR net, the resultant net supervisor is live due to Algorithm 1 or 2.

Proof: It is trivial based on the theorems 5 and 6. ♦

5. Experimental Results

A number of experiments have been conducted. Figures 2-5 represent four different size S^3PR nets. In Fig. 2, it has 3 SMS and 2 elementary siphons. To make the net in Fig. 2 be controlled and live, there are two methods: 1) three control places to be added according to Ezpeleta's Policy; and 2) two control places to be added according to the proposed policy. Tables 1 and 2 show the results of the two methods for the net in Fig. 1, respectively.

The net in Fig. 3 has 18 SMS (S_1-S_{18}) and 6 of them are elementary ones (S_1-S_6). Through the computation, we can get the 18 SMS. They are:

$S_1 = \{p_9, p_{13}, p_{17}, p_{21}, p_{22}, p_{24}, p_{26}\}$

$S_2 = \{p_9, p_{13}, p_{19}, p_{20}, p_{21}, p_{22}, p_{23}, p_{24}, p_{25}, p_{26}\}$

$S_3 = \{p_9, p_{13}, p_{18}, p_{21}, p_{22}, p_{24}, p_{25}, p_{26}\}$

$S_4 = \{p_5, p_8, p_{13}, p_{19}, p_{20}, p_{21}, p_{23}, p_{24}, p_{25}, p_{26}\}$

$S_5 = \{p_5, p_8, p_{13}, p_{18}, p_{21}, p_{24}, p_{25}, p_{26}\}$

$S_6 = \{p_5, p_8, p_{13}, p_{17}, p_{21}, p_{24}, p_{26}\}$

$S_7 = \{p_5, p_7, p_{13}, p_{19}, p_{20}, p_{21}, p_{23}, p_{24}, p_{25}\}$

$S_8 = \{p_5, p_7, p_{13}, p_{18}, p_{21}, p_{24}, p_{25}\}$

$S_9 = \{p_5, p_7, p_{13}, p_{17}, p_{21}, p_{24}\}$

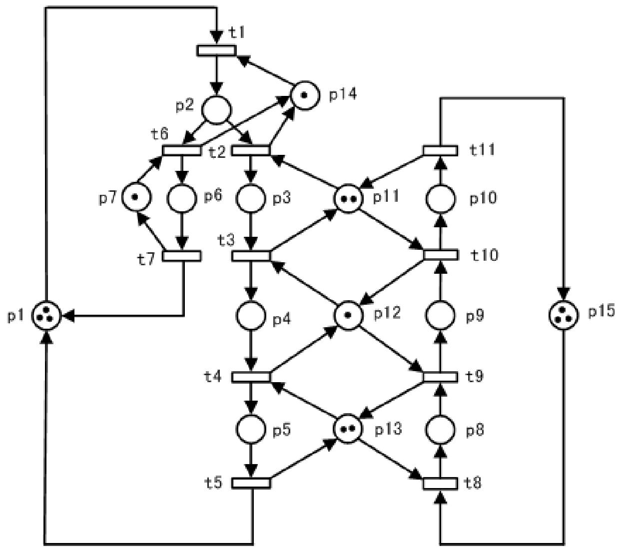

Fig. 2. A simple model.

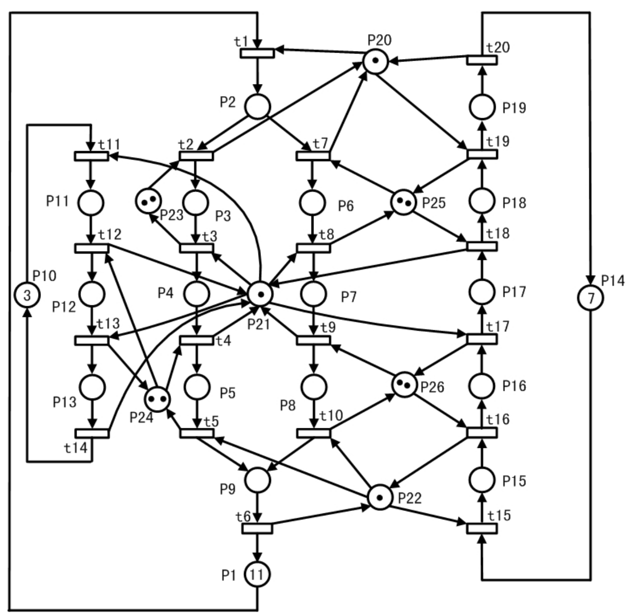

Fig. 3. A plant model

S_{10}={p_4, p_9, p_{11}, p_{13}, p_{19}, p_{20}, p_{21}, p_{22}, p_{23}, p_{25}, p_{26}}
S_{11}={p_4, p_9, p_{11}, p_{13}, p_{18}, p_{21}, p_{22}, p_{25}, p_{26}}
S_{12}={p_4, p_9, p_{11}, p_{13}, p_{17}, p_{21}, p_{22}, p_{26}}
S_{13}={p_9, p_{16}, p_{22}, p_{26}}
S_{14}={p_4, p_7, p_{11}, p_{13}, p_{19}, p_{20}, p_{21}, p_{23}, p_{25}}
S_{15}={p_4, p_7, p_{11}, p_{13}, p_{18}, p_{21}, p_{25}}
S_{16}={p_4, p_8, p_{11}, p_{13}, p_{19}, p_{20}, p_{21}, p_{23}, p_{25}, p_{26}}
S_{17}={p_4, p_8, p_{11}, p_{13}, p_{18}, p_{21}, p_{25}, p_{26}}
S_{18}={p_4, p_8, p_{11}, p_{13}, p_{17}, p_{21}, p_{26}}

We can obtain 6 elementary siphons as follows:

S_1={p_9, p_{13}, p_{17}, p_{21}, p_{22}, p_{24}, p_{26}}
S_2={p_9, p_{13}, p_{19}, p_{20}, p_{21}, p_{22}, p_{23}, p_{24}, p_{25}, p_{26}}
S_3={p_9, p_{13}, p_{18}, p_{21}, p_{22}, p_{24}, p_{25}, p_{26}}
S_4={p_5, p_8, p_{13}, p_{19}, p_{20}, p_{21}, p_{23}, p_{24}, p_{25}, p_{26}}
S_5={p_5, p_8, p_{13}, p_{18}, p_{21}, p_{24}, p_{25}, p_{26}}
S_6={p_5, p_8, p_{13}, p_{17}, p_{21}, p_{24}, p_{26}}

According to the proposed policy, the characteristic T-vectors of other 12 dependent siphons can be expressed by that of the 6 elementary siphons. The coefficient matrix [a] is:

$$[a]=\begin{bmatrix} 1&0&0&1&0&0\\ 1&0&0&0&1&0\\ 0&1&0&1&0&1\\ 0&1&0&0&1&1\\ 0&1&0&0&0&1\\ 0&1&0&1&0&0\\ 0&1&0&0&1&0\\ 0&0&1&1&0&1\\ 0&0&1&0&1&1\\ 0&0&1&0&0&1\\ 0&0&0&1&0&1\\ 0&0&0&0&1&1 \end{bmatrix}$$

For elementary siphon S_1={p_9, p_{13}, p_{17}, p_{21}, p_{22}, p_{24}, p_{26}}, Due to Theorem 1, we add a monitor V_{S1} for it. By Ezpeleta's Policy, we have $^{\bullet}Vs_1$={t_5, t_{10}, t_{13}, t_{17}}, $Vs_1^{\bullet}$={t_1, t_{11}, t_{15}}, $M_0(Vs_1)$=5, and ξ_1=1. By the proposed policy, we have $^{\bullet}Vs_1$={t_5,t_{10},t_{13}, t_{17}}, $Vs_1^{\bullet}$={t_1, t_{11}, t_{15}}, $M_0(Vs_1)$=5, and ξ_1=1.

As done above, Vs_2-Vs_{18} can be accordingly added by Ezpeleta's Policy, and Vs_2-Vs_6 are added by Elementary Siphon Based Policy. Therefore, we can get the results by Ezpeleta's Policy and our Elementary Siphon Based on the Policy. Tables 3 and 4 show the results.

Now consider Fig. 4 that models a production cell. The cell is composed of 5 robots (R1, R2, R3, R4, and R5 can hold a product at a time, respectively) and 7 machines (M1, M2, M3, M4, M5, M6, and M7 can hold two products at a time, respectively). There are 5 loading buffers (I1, I2, I3, I4, and I5) and 5 unloading buffers (O1, O2, O3, O4, and O5) for loading and unloading the cell.

In Fig. 4, there are 70 unmarked strict minimal siphons. To make it live, we can add control places to it. Using Ezpeleta's method, we have to add 70 control places. While using the proposed policy, we only add the 10 control places as shown in the Table 5.

In Fig. 5, there are 169 unmarked strict minimal siphons and 13 elementary siphons that acquire 13 control places to make the net live as shown in Table 6.

Table 1. Required Monitors using Ezpeleta's Policy.

i	$Vs_i^{\bullet}$	$^{\bullet}Vs_i$	$M_{0A}(Vs_i)$
1	{t_1, t_8}	{t_3, t_6, t_{10}}	2
2	{t_1, t_8}	{t_4, t_6, t_9}	2
3	{t_1, t_8}	{t_4, t_6, t_{10}}	4

Table 2. Required Monitors using Elementary Siphon Based Policy.

i	$Vs_i^{\bullet}$	$^{\bullet}Vs_i$	$M_{0A}(Vs_i)$
1	{t_1, t_8}	{t_3, t_6, t_{10}}	1
2	{t_1, t_8}	{t_4, t_6, t_9}	1

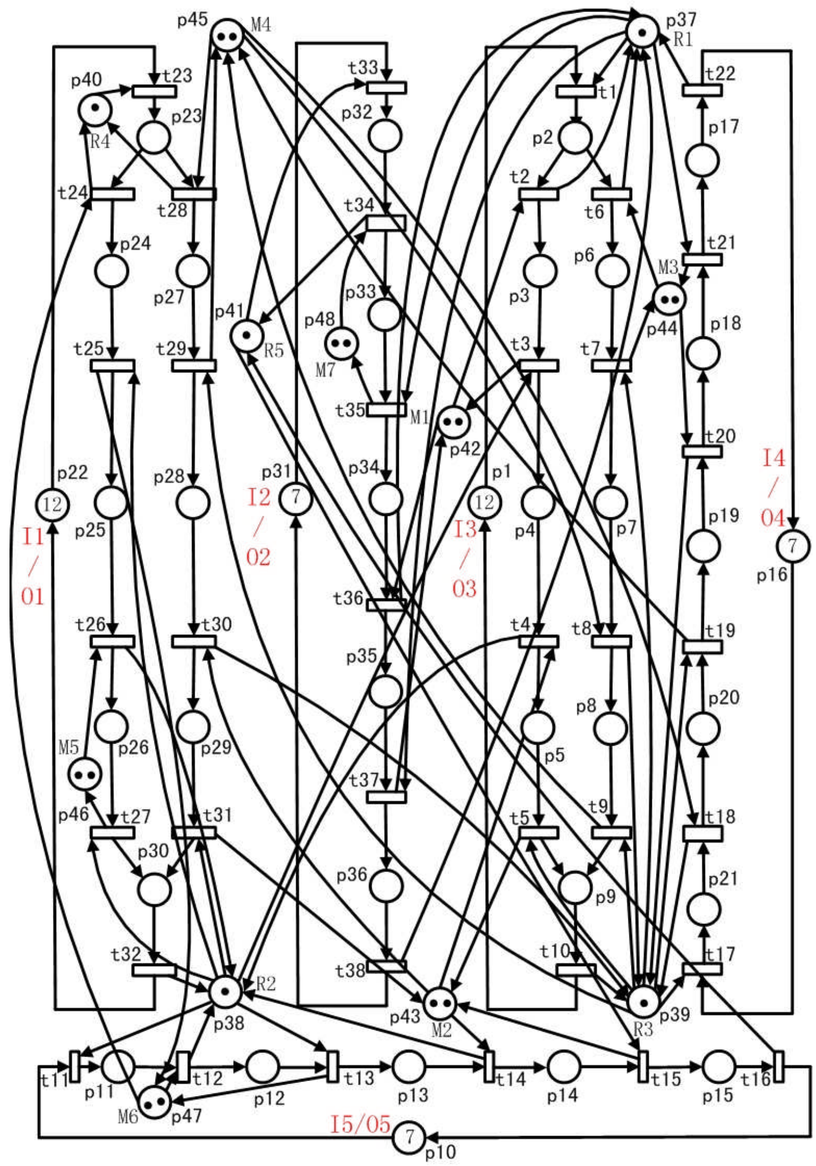

Fig. 4. A plant model for FMS

Table 3. Required Monitors using Ezpeleta's Policy.

i	$Vs_i^{\bullet}$	${}^{\bullet}Vs_i$	$M_{0A}(Vs_i)$
1	$\{t_1, t_{11}, t_{15}\}$	$\{t_5, t_{10}, t_{13}, t_{17}\}$	5
2	$\{t_1, t_{11}\}$	$\{t_4, t_7, t_{13}\}$	2
3	$\{t_1, t_{15}\}$	$\{t_2, t_{10}, t_{16}\}$	2
4	$\{t_1, t_{15}\}$	$\{t_3, t_8, t_{19}\}$	5
5	$\{t_1, t_{15}\}$	$\{t_2, t_8, t_{18}\}$	2
6	$\{t_1, t_{15}\}$	$\{t_2, t_9, t_{17}\}$	2
7	$\{t_1, t_{11}, t_{15}\}$	$\{t_5, t_{10}, t_{13}, t_{19}\}$	10
8	$\{t_1, t_{11}, t_{15}\}$	$\{t_5, t_{10}, t_{13}, t_{18}\}$	7
9	$\{t_1, t_{11}, t_{15}\}$	$\{t_4, t_9, t_{13}, t_{19}\}$	9
10	$\{t_1, t_{11}, t_{15}\}$	$\{t_4, t_9, t_{13}, t_{18}\}$	6
11	$\{t_1, t_{11}, t_{15}\}$	$\{t_4, t_9, t_{13}, t_{17}\}$	4
12	$\{t_1, t_{11}, t_{15}\}$	$\{t_4, t_8, t_{13}, t_{19}\}$	7

Table 3 continued

13	$\{t_1, t_{11}, t_{15}\}$	$\{t_4, t_8, t_{13}, t_{18}\}$	4
14	$\{t_1, t_{15}\}$	$\{t_3, t_{10}, t_{19}\}$	8
15	$\{t_1, t_{15}\}$	$\{t_2, t_{10}, t_{18}\}$	5
16	$\{t_1, t_{15}\}$	$\{t_2, t_{10}, t_{17}\}$	3
17	$\{t_1, t_{15}\}$	$\{t_3, t_9, t_{19}\}$	7
18	$\{t_1, t_{15}\}$	$\{t_2, t_9, t_{18}\}$	4

Table 4. Required Monitors using Elementary Siphon Based Policy.

i	$Vs_i^{\bullet}$	${}^{\bullet}Vs_i$	$M_{0A}(Vs_i)$
1	$\{t_1, t_{11}, t_{15}\}$	$\{t_5, t_{10}, t_{13}, t_{17}\}$	5
2	$\{t_1, t_{11}\}$	$\{t_4, t_7, t_{13}\}$	1
3	$\{t_1, t_{15}\}$	$\{t_2, t_{10}, t_{16}\}$	1
4	$\{t_1, t_{15}\}$	$\{t_3, t_8, t_{19}\}$	4
5	$\{t_1, t_{15}\}$	$\{t_2, t_8, t_{18}\}$	1
6	$\{t_1, t_{15}\}$	$\{t_2, t_9, t_{17}\}$	1

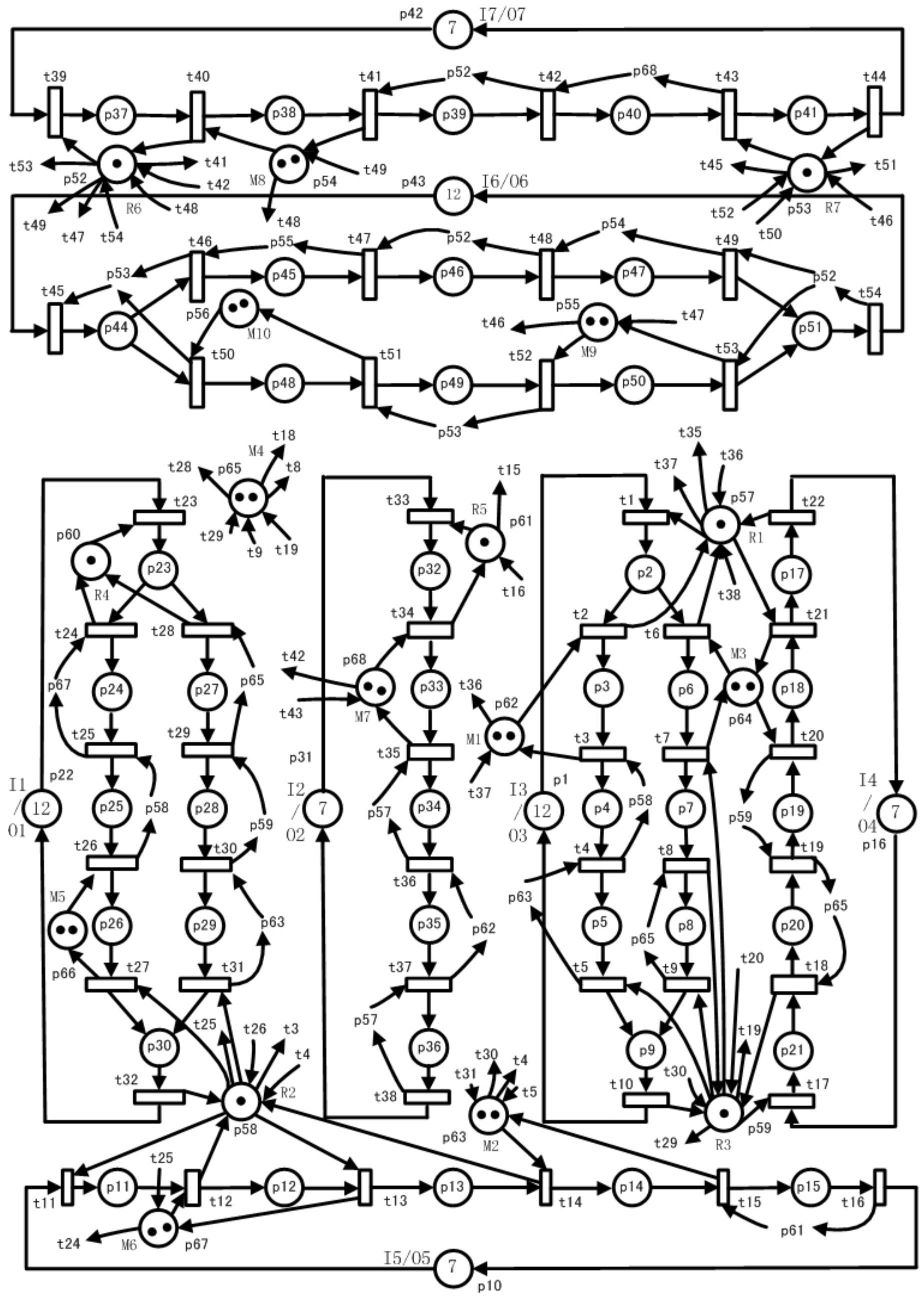

Fig. 5. The Petri net model (N, M_0) of an FMS

Table 5. Required Monitors using Elementary Siphon Based Policy.

i	$V_{S_i}^{\bullet}$	${}^{\bullet}V_{S_i}$	$M_{0A}(V_{S_i})$
1	$\{t_1, t_{17}, t_{23}\}$	$\{t_2, t_9, t_{19}, t_{24}, t_{29}\}$	2
2	$\{t_1, t_{11}, t_{17}, t_{23}\}$	$\{t_5, t_7, t_{14}, t_{21}, t_{24}, {}_{31}, t_{37}\}$	8
3	$\{t_1, t_{11}, t_{23}\}$	$\{t_4, t_6, t_{14}, t_{24}, t_{31}\}$	2
4	$\{t_1, t_{11}, t_{23}, t_{33}\}$	$\{t_4, t_6, t_{15}, t_{24}, t_{31}, t_{37}\}$	8
5	$\{t_{11}, t_{23}\}$	$\{t_{13}, t_{25}, t_{28}\}$	1
6	$\{t_{23}\}$	$\{t_{27}, t_{28}\}\}$	1
7	$\{t_{33}\}$	$\{t_{37}\}$	1
8	$\{t_1, t_{17}, t_{23}\}$	$\{t_2, t_7, t_{20}, t_{24}, t_{30}\}$	1
9	$\{t_1, t_{23}\}$	$\{t_5, t_6, t_{24}, t_{30}\}$	2
10	$\{t_1, t_{17}, t_{33}\}$	$\{t_2, t_6, t_{21}, t_{37}\}$	3

Table 6. Required Monitors using Elementary Siphon Based Policy.

i	$V_{S_i}^{\bullet}$	${}^{\bullet}V_{S_i}$	$M_{0A}(V_{S_i})$
1	$\{t_{39}, t_{45}\}$	$\{t_{41}, t_{49}, t_{50}\}$	1
2	$\{t_{39}, t_{45}\}$	$\{t_{43}, t_{47}, t_{53}\}$	3
3	$\{t_{33}\}$	$\{t_{37}\}$	1
4	$\{t_1, t_{11}, t_{17}, t_{23}, t_{33}\}$	$\{t_5, t_7, t_{14}, t_{21}, t_{24}, t_{31}, t_{37}\}$	5
5	$\{t_1, t_{11}, t_{23}, t_{33}\}$	$\{t_4, t_6, t_{15}, t_{24}, t_{31}, t_{37}\}$	5
6	$\{t_1, t_{11}, t_{23}\}$	$\{t_4, t_6, t_{14}, t_{24}, t_{31}\}$	1
7	$\{t_{23}\}$	$\{t_{27}, t_{28}\}$	1
8	$\{t_{11}, t_{23}\}$	$\{t_{13}, t_{25}, t_{28}\}$	1
9	$\{t_1, t_{23}\}$	$\{t_5, t_6, t_{24}, t_{30}\}$	1
10	$\{t_1, t_{17}\}$	$\{t_2, t_7, t_{20}\}$	1
11	$\{t_1, t_{17}, t_{23}\}$	$\{t_2, t_9, t_{19}, t_{24}, t_{29}\}$	1
12	$\{t_{39}, t_{45}\}$	$\{t_{43}, t_{47}, t_{53}\}$	4
13	$\{t_1, t_{17}, t_{33}\}$	$\{t_2, t_6, t_{21}, t_{37}\}$	2

Through the above analysis, we can get Table 7 that compares the performance of the two algorithms.

Table 7. Comparison of Two Methods.

System	Number of Control Places added	Number of Arcs added	Policy
Fig. 1	3 / 2	15 / 10	Ezpeleta's Policy / Elementary Siphon's Policy
Fig. 2	18 / 6	106 / 32	
Fig. 3	70 / 10	686 / 68	
Fig. 4	169 / 13	2255 / 81	

6. CONCLUSION

A structural analysis has been performed for the design of liveness-enforcing Petri net supervisors for FMS through four different scaled examples. The results show that the elementary siphons based method can always leads to structurally simple Petri net supervisors that have the same deadlock control purpose. That is to say, using the same deadlock control policy, we can get a structurally simple liveness-enforcing Petri net supervisor if the existence of elementary siphons is taken into account. The future work includes developing some effective and efficient deadlock prevention policies based on elementary siphons in a Petri net. More industrial-size FMS are desired and should be used to benchmark various deadlock control methods.

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