ONE NOVEL COMPUTATIONALLY IMPROVED OPTIMAL CONTROL POLICY FOR DEADLOCK PROBLEMS OF FLEXIBLE MANUFACTURING SYSTEMS USING PETRI NETS

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ABSTRACT
Petri nets have been proven to be very useful in the modeling, analysis, simulation, and control of flexible manufacturing systems (FMS). The first reason is conflicts and buffer sizes can be modeled easily and efficiently. The other one is deadlock in this system can then be detected effortlessly. Therefore, how to solve the deadlock problem is an important issue in this domain. In existing literature, theory of regions is viewed one powerful method for obtaining maximally permissive controllers. All legal and live maximal behavior of Petri net models can be preserved by using marking/transition-separation instances (MTSIs) technology. However, computing all sets of MTSIs is an extremely time consuming problem. Additionally, computing linear programming program (LPP) is another serious time consuming problem. In our previous works, crucial MTSI (CMTSI) concept is first proposed to improve the computational cost. In this paper, the selective siphon method and reduction technology are merged in our new deadlock prevention policy. The merit of the proposed policy is that the number CMTSIs can then be simplified further. Experimental results indicate that it is the most efficient policy to obtain maximal permissive behavior of Petri net models.

KEY WORDS
Petri nets, flexible manufacturing system, deadlock prevention, theory of regions.

1. Introduction
Petri nets have been recognized as one of the most powerful tools for modeling flexible manufacturing systems (FMSs) [1]. The main reason is conflicts and buffer sizes in FMSs can be modeled easily and efficiently. Additionally, deadlock in FMSs can also be detected effortlessly by using Petri nets theory. Therefore, how to solve the deadlock problem is an important issue in this domain. In existing literature [13-25], the theory of regions [2] is one very powerful method to obtain system’s maximally permissive liveness.

Uzam [3] further based on the theory of regions to define deadlock-zone (DZ), deadlock-free-zone (DFZ), event-state-separation-problem (ESSP). An optimal (i.e. maximally permissive) controller can be obtained once all ESSPs are processed (e.g. deadlock-free) in a deadlock system. However, its disadvantage is that same control places are obtained by numerous of ESSPs).

On the other hand, Ghaffari et al. [4] define legal marking, dangerous markings, forbidden markings, and the set of Marking/Transition-Separation Instance (MTSI) based on the theory of regions. Under the MTSI method, one optimal deadlock prevention policy is also proposed. Unfortunately, the main disadvantage is still that same control places are obtained by numerous of MTSIs.

In [7], Crucial MTSI (CMTSI) concept first developed. It improves the efficiency of conventional MTSI method. However, only one type CMTSI is defined. In [9], two types CMTSIs are proposed formally. Two type CMTSIs can cover all MTSIs. The computational cost is hence reduced further. In [8], the reduction technology [1] is merged into the CMTSI method so as to Linear Programming Program (LPP) is reduced since reachability graph is simplified.

In this paper, the selective siphon method and reduction technology are merged in our new deadlock prevention policy. The advantage of the proposed method is that the number of two types CMTSI can then be simplified. The LPP is also reduced. The detailed steps are as follows. First of all, reachability graph is still needed. Second, the reduction technology is used to simply the construct of system. Third, CMTSIs are identified. Further, selective siphons method is adopted to check if all dead/quasi-dead markings of CMTSIs are covered by these selective siphons. Furthermore, choose anyone CMTSI that belongs to a same selective siphon to be processed. Finally, controllers are therefore obtained. Experimental results indicate that it is the most efficient policy to obtain maximal permissive behavior of Petri net models.

The rest of this paper is organized as follows. Section II presents the basic definitions and properties of the theory of regions, MTSI and critical markings. Section III then describes the proposed deadlock prevention policy. Next, Section IV presents the experimental results. Section V gives the comparisons. Conclusions are made in Section VI.
2. Preliminaries

2.1 Petri Nets [1]

A PN is a 5-tuple, \( PN = (P, T, F, W, M_0) \) where \( P \) is a finite set of places; \( T \) is a finite set of transitions, with \( P \cap T \neq \emptyset \) and \( P \cap T = \emptyset \); \( F \subseteq (P \times T) \cup (T \times P) \) is the set of all directed arcs, \( W : (P \times T) \cup (T \times P) \rightarrow N \) is the weight function where \( N = \{ 0, 1, 2, \ldots \} \), and \( M_0 : P \rightarrow N \) is the initial marking. \( N \) is said to be ordinary, denoted as \( (P, T, F) \), if \( \forall f \in F, W(f) = 1 \). \( N'(p, t) = W(p, t) \) is the input function that means the multiplicity of a directed arc from \( p \) to \( t \) if \( (p, t) \in F \). \( N(p, t) = W(t, p) \) is the output function that means the multiplicity of a directed arc from \( t \) to \( p \) if \( (t, p) \in F \). The set of input (resp., output) transitions of a place \( p \) is denoted by \( \cdot \) (resp., \( \cdot \)). Similarly, the set of input (resp., output) places of a transition \( t \) is denoted by \( \cdot \) (resp., \( \cdot \)). A PN structure \( (P, T, F, W) \) is denoted by \( N \). A PN with a given initial marking is denoted by \( (N, M_0) \).

A PN is said to be pure if no places are both input and output places of the same transition. The so-called incidence matrix \( [N] \) of a pure PN is defined as \( [N] = [N] - [N]' \). A transition \( t \) is said to be enabled at marking \( M \), if \( \forall p \in \cdot t, M(p) \geq W(p, t) \) or \( p \) is marked with at least \( W(p, t) \) tokens, as denoted by \( M \mid t \rangle \). A transition may fire if it is enabled. In an ordinary net, it is enabled iff \( \forall p \in \cdot t, M(p) \geq 1 \). Firing \( t \) at \( M \) gives a new marking \( M' \) such that \( \forall p \in P, M'(p) = M(p) - W(p, t) + W(t, p) \). It is denoted as \( M \mid t \rangle M' \). \( M \) indicates the number of tokens in each place, which means the current state of the modeled system. When marking \( M_0 \) can be reached from \( M_0 \) by firing a sequence of transitions \( \sigma \), this process is denoted by \( M \mid \sigma \rangle M_0 \) and satisfies the state equation \( M_\sigma = M + [N] \hat{\sigma} \). Here, \( \hat{\sigma} \) is a vector of non-negative integers, called counting vector, and \( \hat{\sigma}(i) \) indicates the algebraic sum of all occurrences of \( \sigma \) in \( \hat{\sigma} \). The set of all reachable markings for a PN given \( M_0 \) is denoted by \( R(N, M_0) \).

A transition \( t \) is said to be live if for any \( M \in R(N, M_0) \), there exists a sequence of transitions whose firing leads to \( M' \) that enables \( t \). A PN is said to be live if all the transitions are live. Liveness of a PN means that for each marking \( M \in R(N, M_0) \) reachable from \( M_0 \), it is finally possible to fire \( t \), \( \forall t \in T \) through some firing sequence. \( (N, M_0) \) is said to be reversible, if for each marking \( M \in R(N, M_0) \), \( M_0 \) is reachable from \( M \). Thus, in a reversible net it is always possible to go back to initial marking (state) \( M_0 \). A marking \( M' \) is said to be a home state, if for each marking \( M \in R(N, M_0) \), \( M' \) is reachable from \( M \). Reversibility is a special case of the home state property, i.e. if the home state \( M' = M_0 \), the net is reversible. A PN contains a deadlock if there is a marking \( M \in R(N, M_0) \) at which no transition is enabled. Such a marking is called a dead marking. Deadlock situations are as a result of inappropriate resource allocation policies or exhaustive use of some or all resources.

2.2 The Reduction Approach of Petri Nets [1]

Petri nets reduction approach is a well-known technology to derive the properties of a complex PN model, while preserving the concerned properties, such as boundedness, liveness and reversibility. By simplifying the PN structure, it is an efficient analysis way to derive the properties of a complex PN model. In this section, six simple reduction rules which are taken form [1] are considered. They are depicted in Figure 1(a)-(f): (a) Fusion of series places; (b) Fusion of series transitions (c) Fusion of parallel places (d) Fusion of parallel transitions. (e) Elimination of self-loop places (f) Elimination of self-loop transitions.

In short, we assume that \((N, M_0)\) is an original PN and \((N', M_0')\) is the simplified PN. One can infer that \((N', M_0')\) is live, safe, and bounded iff \((N, M_0)\) is live, safe, and bounded, respectively [1].

![Image of reduction rules in Petri net](image_url)

Figure 1. The Six kinds of reduction rules in Petri net.

2.3 The Theory of Regions [4]

Due to limitation of paper space, the detailed theory of Petri net please refers to [4]. In this subsection, three kinds of equation are shown as follows. Equation (1) is reachability condition equation, equation (2) is cycle equation, and equation (3) is event separation condition equation. Please note that Eq. (3) is formed from MTSI. And, equations (1)-(3) represents all control places \( p_i \) must satisfy reachability condition of the legal behavior, cycle equations, and the event separation condition of \( (M, t) \). The three conditions are listed below.

\[
M(p_i) = M_0(p_i) + [N](p_i, t) \hat{\gamma}(N) \geq 0, \forall M \in M_L \tag{1}
\]

\[
\sum_{i \in I} [N](p_i, t) \hat{\gamma}(N) = 0, \forall \gamma \in C \tag{2}
\]

\[
M_0(p_i) + [N](p_i, t) \hat{\gamma}(N) + [N](p_i, t) \leq -1 \tag{3}
\]

2.4 Crucial MTSI (CMTSI)

In our previous work [7], we first proposed the concept of CMTSI. One only identifies CMTSIs to replace all MTSIs. And also it can make the dead-prone PN model alive. In [9], two types of CMTSIs are introduced. The detailed information please refers to [9], this work just
shows the main definitions.

**Definition 1:** Type I CMTSI: \( \Omega' = \{(M, t) | M \in M_\triangle, t \in T, \exists M' \in M_\triangle, \text{ such that } M'[t > M'] \}. \) Denote the set of all the dead markings related to \( \Omega' \) as \( M'_D \), i.e. \( M'_D = \{M' | M' \in M_\triangle, \exists (M, t) \in \Omega' \text{ such that } M'[t > M'] \}. \)

**Definition 2:** Type II CMTSI: \( \Omega'' = \{(M, t) | M \in M_\triangle, t \in T, \exists M' \in M_\triangle, M'' \in M_\triangle, \text{ and a firing sequence } \sigma = \sigma'(M') \rightarrow M'' \text{ from } M' \text{ to } M'' \text{ such that } M'[t > M'] \text{ and } M''[\sigma > M''] \}. \) The set of dead markings associated with type II CMTSI is denoted as \( M''_D \), called type II deadlocks. \( M''_D = \{M'' | M'' \in M_\triangle, \exists (M, t) \in \Omega'', M' \in M_\triangle, \text{ and a firing sequence } \sigma \text{ from } M' \text{ to } M'' \text{ such that } M'[t > M'] \text{ and } \sigma = \sigma'(M'') \} \).

**Remark 1:** Type I CMTSI should be processed first.

### 2.5 The Relation between Critical Markings and Selective Siphons [5-6]

Pirotti et al. [5-6] proposed the selective siphon control approach. The key of the policy is that the relations between uncontrolled siphons and critical markings need to be identified and then a set of siphons is selected by solving a set covering problem at each iteration. Once the selected siphons are controlled, all the paths from legal markings to either selected siphons or critical markings are accordingly forbidden. In other words, one selective siphon can control two (or above two) critical markings if those critical markings are included in the same minimal siphon. Besides, its most attractive advantage is that it also can hold the maximally permissive markings. In this paper, the selective siphon control approach is merged into our previous policy to further reduce the number of CMTSIs.

In the following, uncontrolled siphons, critical markings, and selected siphons are defined.

**Definition 3:** Uncontrolled siphons and critical markings: Let \( \Pi = \{S_1, \ldots, S_n\} \) the set of minimal siphons of \( PN \).

i) The set \( \Pi_u = \{S_j \in \Pi | E_j \neq \emptyset\} \), where \( E_j = \{M \in R(N, M_0) | \lambda_j M = 0\} \), is the set of uncontrolled siphons.

ii) The set \( \Pi_\emptyset = \{S_j \in \Pi_u | \lambda_j M = 0\} \) denotes the set of empty siphons in the marking \( M \).

iii) For any \( \Pi' \subseteq \Pi_u \), \( E_{\Pi'} = \bigcup_{S_j \in \Pi'} E_j \) is the set of markings where at least one siphon in \( \Pi' \) is empty.

iv) The set \( E_{\Pi_\emptyset} \) denotes the set of critical markings.

v) A covering set of uncontrolled siphons (CSUS) is a subset of siphons \( \Pi_c \subseteq \Pi_u \) such that \( E_{\Pi_c} = E_{\Pi_\emptyset} \).

Please note that, the relation between Critical Markings and Selective Siphons will be used in the proposed deadlock prevention policy to check if the CMTSI belong to the same siphon. Section 3 will show how the method is used in the algorithm of the proposed novel computational improved control policy.

### 3. One Novel Computationally Improved Control Policy

**Definition 4:** Two CMTSIs (or above two) belong to critical CMTSI (CCMTSI) once they can be included in same selective siphons.

**Table 1:** The relations between Selective siphons and CMTSIs

<table>
<thead>
<tr>
<th>MTSI</th>
<th>CMTSI A</th>
<th>CMTSI B</th>
<th>CMTSI C</th>
<th>CMTSI D</th>
<th>CMTSI E</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 )</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
</tr>
<tr>
<td>( S_3 )</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
</tr>
</tbody>
</table>

For example, based on Table 1, there should be five CMTSI needed to process. Further, it is obvious that CMTSI A and CMTSI B are included in the empty siphon \( S_1 \). Similarly, CMTSI C and CMTSI D are included in the empty siphon \( S_2 \). According to Definition 4, therefore, CMTSI A and CMTSI B can be viewed the same set of the CCMTSI X and CMTSI C and CMTSI D can be viewed the same set of the CCMTSI Y. As a result, there are just three CMTSIs needed to process after the CCMTSI tracking algorithm is used.

**Remark 2:** One single CMTSI which does not be included in any empty Siphon must still be processed.

### 3.1. New Deadlock Prevention Algorithms

Given a deadlock-prone PN model, design steps are listed as shown below.

1. Generate \( R(N, M_0) \).
2. Reduction technology is used to simplify construct of system.
3. Determine the total number of dead markings.
4. Identify all dead, quasi-dead, and legal markings.
5. Find \( \Omega' \). If all dead markings belong to \( \Omega' \) go to 6. Find \( \Omega'' \).
6. Determine and identify uncontrolled siphons.
7. Locate selective siphons.
8. IF all dead/quasi-dead markings of CMTSIs \( \Omega' \cup \Omega'' \) are covered by one empty siphons.
   THEN
   One can choose anyone CMTSI that belongs to a same selective siphon to be processed.
   ELSE
   Others CMTSIs that are not covered by the selective siphons must be considered.
9. Generate the event separation condition equations of all CMTSIs.
10. List the sets of the oriented cycles of the reachability graph.
11. Generate all legal reachability condition equations of the reachability graph except quasi-dead markings and dead markings.
14. Identify and remove those redundant control places to obtain the live controlled net.

4. Example

One typical model shown in Figure 2 [10] is employed as an example. In this example, 16 dead markings, 61 quasi-dead markings, and 205 legal markings are in its reachability graph. In other words, the number of maximally permissive markings is 205. Please note that, therefore, there should be 205 LPP needed to consider since 205 legal markings will be formed 205 reachability condition equations.

To do so, first of all, the reduction approach is used. After the reduction rules, $p_7$ and $p_{13}$ are deleted, and $t_7$ and $t_{13}$ are connected with $f_8$ and $t_{14}$, respectively based on fusion of series transitions. Therefore, one can then obtain a reduced S’PR [13] model shown in Figure 3.

![Figure 2. One typical PN model.](image)

![Figure 3. The reduced model of this example.](image)

In the following, 176 reachable markings ($M_1$ to $M_{176}$) can be identified in its reachability graph for this example. The 16 dead markings (i.e. $M_{68}$, $M_{69}$, $M_{125}$, $M_{130}$, $M_{134}$, $M_{137}$, $M_{62}$, $M_{153}$, $M_{154}$, $M_{162}$, $M_{170}$, $M_{171}$, $M_{172}$, $M_{174}$, and $M_{176}$) can then be located by using software INA [11]. Additionally, quasi-dead markings $M_{26}$, $M_{55}$, $M_{42}$, $M_{52}$, $M_{59}$, $M_{68}$, $M_{72}$, $M_{75}$, $M_{79}$, $M_{85}$, $M_{69}$, $M_{106}$, $M_{107}$, $M_{111}$, $M_{116}$, $M_{118}$, $M_{119}$, $M_{120}$, $M_{124}$, $M_{126}$, $M_{127}$, $M_{136}$, $M_{138}$, $M_{141}$, $M_{142}$, $M_{143}$, $M_{144}$, $M_{150}$, $M_{151}$, $M_{155}$, $M_{159}$, $M_{162}$, $M_{164}$, $M_{166}$, $M_{168}$, $M_{169}$, and $M_{173}$ are found. Hence, the number of legal markings (i.e. 176 – (16 + 41) = 119) can then be determined. In other words, the number of optimal (maximally permissive) legal markings is 119.

Besides, 7 sets of type I CMTSIs (i.e. $\{M_{67}, t_1\}$, $\{M_{105}, t_0\}$, $\{M_{115}, t_1\}$, $\{M_{130}, t_0\}$, $\{M_{140}, t_0\}$, $\{M_{166}, t_1\}$, and $\{M_{165}, t_1\}$) are identified. Further, 11 sets of type II CMTSIs (i.e. $\{M_{34}, t_{11}\}$, $\{M_{77}, t_{11}\}$, $\{M_{123}, t_0\}$, $\{M_{115}, t_{11}\}$, $\{M_{123}, t_{11}\}$, $\{M_{165}, t_{11}\}$, $\{M_{64}, t_{11}\}$, $\{M_{64}, t_{11}\}$, $\{M_{64}, t_{11}\}$, and $\{M_{148}, t_{11}\}$) are also identified.

Table 2: The relation between CMTSI and empty siphons

<table>
<thead>
<tr>
<th>CMTSI No.</th>
<th>Type I or II</th>
<th>Siphon No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>${M_{67}, t_1}$</td>
<td>Type I</td>
<td>$S_2$</td>
</tr>
<tr>
<td>${M_{105}, t_0}$</td>
<td>Type I</td>
<td>$S_2$</td>
</tr>
<tr>
<td>${M_{115}, t_1}$</td>
<td>Type I</td>
<td>$S_2$</td>
</tr>
<tr>
<td>${M_{130}, t_0}$</td>
<td>Type I</td>
<td>$S_3$</td>
</tr>
<tr>
<td>${M_{140}, t_0}$</td>
<td>Type I</td>
<td>$S_3$</td>
</tr>
<tr>
<td>${M_{165}, t_1}$</td>
<td>Type I</td>
<td>$S_2$</td>
</tr>
<tr>
<td>${M_{166}, t_1}$</td>
<td>Type I</td>
<td>$S_1$</td>
</tr>
<tr>
<td>${M_{34}, t_{11}}$</td>
<td>Type II</td>
<td>$S_1$</td>
</tr>
<tr>
<td>${M_{77}, t_{11}}$</td>
<td>Type II</td>
<td>$S_1$</td>
</tr>
<tr>
<td>${M_{123}, t_0}$</td>
<td>Type II</td>
<td>None</td>
</tr>
<tr>
<td>${M_{115}, t_{11}}$</td>
<td>Type II</td>
<td>$S_1$</td>
</tr>
<tr>
<td>${M_{123}, t_{11}}$</td>
<td>Type II</td>
<td>$S_1$</td>
</tr>
<tr>
<td>${M_{165}, t_{11}}$</td>
<td>Type II</td>
<td>$S_1$</td>
</tr>
<tr>
<td>${M_{64}, t_{11}}$</td>
<td>Type II</td>
<td>$S_2$</td>
</tr>
<tr>
<td>${M_{64}, t_{11}}$</td>
<td>Type II</td>
<td>None</td>
</tr>
<tr>
<td>${M_{64}, t_{11}}$</td>
<td>Type II</td>
<td>$S_1$</td>
</tr>
<tr>
<td>${M_{148}, t_{11}}$</td>
<td>Type II</td>
<td>$S_1$</td>
</tr>
</tbody>
</table>

Table 3: Six control places in this example.

<table>
<thead>
<tr>
<th>Control Place ($C_p$)</th>
<th>$M_0(C_p)$</th>
<th>$(C_{pi})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{p1}$</td>
<td>1</td>
<td>$t_5$, $t_{13}$</td>
</tr>
<tr>
<td>$C_{p2}$</td>
<td>2</td>
<td>$t_6$, $t_{13}$</td>
</tr>
<tr>
<td>$C_{p3}$</td>
<td>3</td>
<td>$t_6$, $t_{11}$</td>
</tr>
<tr>
<td>$C_{p4}$</td>
<td>3</td>
<td>$t_5$, $t_{11}$</td>
</tr>
<tr>
<td>$C_{p5}$</td>
<td>3</td>
<td>$t_7$, $t_{11}$</td>
</tr>
<tr>
<td>$C_{p6}$</td>
<td>4</td>
<td>$t_7$, $t_{11}$</td>
</tr>
</tbody>
</table>

36
And then, three selective siphons (i.e. \( \{p_2, p_5, p_15, p_{18}\} \), \( \{p_2, p_{11}, p_{16}, p_{17}, p_{18}, p_{19}\} \), and \( \{p_{51}, p_{14}, p_{15}, p_{18}\} \) ) can be obtained according to definition 3. In this paper, the first siphon \( \{p_2, p_5, p_{15}, p_{18}\} \) is named \( S_1 \), the second siphon \( \{p_{51}, p_{14}, p_{15}, p_{18}\} \) is named \( S_2 \), and the final siphon \( \{p_2, p_{11}, p_{16}, p_{17}, p_{18}, p_{19}\} \) is named \( S_3 \). It is obvious, therefore, that \( \{M_{54}, t_{11}\} \), \( \{M_{27}, t_{11}\} \), \( \{M_{115}, t_{11}\} \), \( \{M_{64}, t_{11}\} \), \( \{M_{165}, t_{11}\} \), \( \{M_{66}, t_{11}\} \), and \( \{M_{148}, t_{11}\} \) are included in \( S_1 \), \( \{M_{115}, t_{1}\} \), \( \{M_{165}, t_{1}\} \), and \( \{M_{123}, t_{1}\} \) are included in \( S_2 \), and \( \{M_{105}, t_{6}\} \), \( \{M_{139}, t_{6}\} \), \( \{M_{140}, t_{5}\} \), and \( \{M_{165}, t_{5}\} \) are included in \( S_3 \) based on Table 2. Similarly, based on Table 2, one can also find that \( \{M_{123}, t_9\} \) and \( \{M_{64}, t_5\} \) are not included in any empty siphon. Therefore, \( \{M_{123}, t_9\} \) and \( \{M_{64}, t_5\} \) are still necessary considered. In other words, there are three sets of CCMTSIs and two sets of CMTSIs needed to be calculated.

Finally, one can obtain six control places (shown in Table 3) and the system is live after the six control places are added in the reduced system. The original system is live too since the reduced system is live based on the reduction technology [1].

5. Comparison with Previous Policies

There are total six deadlock prevention policies present in table 4. All of them are optimal based on theory of regions. Obviously, based on the table 4, this work presents a computationally improved optimal control algorithm among existing literatures since just 5 sets of MTSI and 119 LPP are needed to solve.

### Table 4: Comparison of the controlled Example IV

<table>
<thead>
<tr>
<th>Control Criteria</th>
<th>No. of Monitors</th>
<th>Reachable Markings</th>
<th>Maximally Permissive?</th>
<th>No. of MTSI</th>
<th>No. of LPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>8</td>
<td>205</td>
<td>Yes</td>
<td>59</td>
<td>205</td>
</tr>
<tr>
<td>[4]</td>
<td>8</td>
<td>205</td>
<td>Yes</td>
<td>59</td>
<td>205</td>
</tr>
<tr>
<td>[9]</td>
<td>6</td>
<td>205</td>
<td>Yes</td>
<td>18</td>
<td>205</td>
</tr>
<tr>
<td>[8]</td>
<td>6</td>
<td>205</td>
<td>Yes</td>
<td>18</td>
<td>119</td>
</tr>
<tr>
<td>[12]</td>
<td>6</td>
<td>205</td>
<td>Yes</td>
<td>5</td>
<td>205</td>
</tr>
<tr>
<td>[This Work]</td>
<td>6</td>
<td>205</td>
<td>Yes</td>
<td>5</td>
<td>119</td>
</tr>
</tbody>
</table>

6. Conclusion

The proposed policy can be implemented for FMSs based on Petri nets, the theory of regions and selective siphon methods, where the dead markings are identified in its reachability graph. For reducing computation cost, a new definition of the MTSIs proposed here, called crucial marking/transition-separation instances (CMTSI) which is the foundation of MTSIs. The proposed policy can reduce the amount of inequality and the computation cost due to the involvement of a few MTSIs. Consequently, several deadlock systems can be controlled successfully. Moreover, a maximally permissive controller with efficient computation can still be implemented based on the experimental data.

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