An Improved Synthesis Method Based on ILPP and Colored Petri Net for Liveness Enforcing Controller of Flexible Manufacturing Systems

HUSAM KAID¹,², ABDULRAHMAN AL-AHMARI¹,², ZHIWU LI³, (Fellow, IEEE), AND WADEA AMEEN⁴

¹Industrial Engineering Department, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia
²Raytheon Chair for Systems Engineering (RCSE Chair), Advanced Manufacturing Institute, King Saud University, Riyadh 11421, Saudi Arabia
³Institute of Systems Engineering, Macau University of Science and Technology, Taipa, Macao 999078, China
⁴Industrial Engineering Department, College of Engineering and Architecture, Al-Yamamah University, Riyadh 11512, Saudi Arabia

Corresponding authors: Husam Kaid (yemenhussam@yahoo.com) and Abdulrahman Al-Ahmari (alahmari@ksu.edu.sa)

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ABSTRACT Petri nets are used to design deadlock control strategies for flexible manufacturing systems (FMSs), which typically involve the addition of monitors and the associated arcs to the FMS. The addition of several monitors and associated arcs to the first constructed Petri net model significantly complicates the Petri net controller. This paper develops a two-step method for preventing deadlocks based on a colored Petri net and a structurally minimal approach that significantly reduces the number of monitors. In the first step, a vector covering technique is applied to generate a minimal covered set of first-met bad markings (FBMs) and legal markings that are respectively smaller than the sets of FBMs and legal markings. At one iteration, place invariants (PIs) corresponding to monitors are constructed by solving an integer linear programming problem (ILPP) to prohibit the maximum number of FBMs, while allowing all legal markings in the minimal covering set. The purpose of the ILPP is to maximize the number of FBMs forbidden by the PIs. Then, based on a colored Petri net, all generated monitors are combined into a global control place. Therefore, a supervisor with minimal structural complexity can be constructed. The obtained net model is controlled after the addition of the designed supervisor. Two instances from the literature are considered to illustrate the proposed approach.

INDEX TERMS Colored Petri nets, integer linear programming, flexible manufacturing system, deadlock prevention.

I. INTRODUCTION A flexible manufacturing system (FMS) executes a variety of tasks through the use of several processes that compete for finite resources including machines, robots, buffers, and fixtures [1], [2]. In an FMS, deadlock can occur as a result of processes competing for system resources [3]. In general, a deadlock causes a system to become inefficient and blocked, and may even result in destructive behavior, which is usually undesirable. As a result, a variety of methods have been developed to address the deadlock problem, including detection and recovery of deadlock [4], [5], avoidance of deadlock [6], [7], and prevention of deadlock [1], [2], [8]–[11].

Petri nets (PNs) are efficient mathematical and graphical modeling, analysis, and control tools for FMS deadlocks [2], [12], [13]. It is used to depict the FMSs’ properties and behaviors, including conflict, sequencing, and synchronization. Additionally, PNs can be applied to represent characteristics such as liveness and boundedness [8]. The advantage of PNs over other modeling and simulation tools such as Arena [14], [15], queuing network models [16], digraph [17], and automata [18] are that they provide a simple representation of the systems. Petri nets are qualified to represent systems top-down at multiple levels of analysis and complexity, and
they have a strong mathematical foundation that permits both qualitative and quantitative study of such systems [9]. Deadlock prevention approaches are being pursued by a number of researchers, which can work as criteria for liveness-enforcing supervisors. These criteria involve behavioral permissiveness, which improves the system’s resource utilization, and structural complexity, which results in a controller with a small number of control places, thus also reducing hardware and software costs, and computational complexity, which permits the implementation of a deadlock control approach to the large-scale systems [9], [10], [19]–[22].

Generally, structural analysis [10], [23], [24] and reachability graph analysis [25]–[27] are used to synthesize deadlock prevention methods based on Petri nets. Structural analysis is a powerful method for overcoming deadlocks in certain types of Petri net structures. In comparison to structural analysis methods, reachability graph-based methods can result in optimal or near-optimal controllers for generalized Petri net systems. Furthermore, these approaches must list all of the system’s reachable states [8], [28], [29]. The purpose of this study is to discuss methods for analyzing reachability graphs. All markings (states) on a system can be classified into two groups, legal and illegal, based on their compliance with a control specification. In the deadlock prevention specification, a marking is considered legal if it or one of its successor states may transition back to the original marking; otherwise, it is an illegal state. A monitor is optimal if it prevents all illegal states while enabling all legal states. In the studies [30], [31], a reachability graph is presented, some of the basic concepts employed in this study [8] proposes a vector covering strategy to solve the above problem by analyzing the relationship between various states.

In this study, we present a strategy for supervisory control based on a controller’s structural minimization. Without the need for iterations, the structurally minimal method is applied to formulate an integer linear programming problem (ILPP). By solving this ILPP, it is possible to achieve a set of optimal or near-optimal monitors while minimizing the monitors. Consequently, the designed monitors are significantly reduced, and the redundancy test is omitted. Finally, by adding a minimal number of monitors, the final net model becomes live. In comparison to previous work [34], our approach enables the development of an optimal or near-optimal supervisor with fewer monitors and without the need for iterations.

The rest of the paper is structured as follows: Section II presents some of the basic concepts employed in this research, including Petri nets, monitor synthesis using a place invariant, and the structurally minimal method. Section III provides a policy for supervisors with simple structures to prevent deadlocks. Several experimental results obtained using the developed approach are shown in Section IV. Finally, Section V presents conclusions and future research.

II. PRELIMINARIES

A. PETRI NETS

A marked Petri net is represented by $N = (P, T, F, W, M_o)$, where

1. $P$: Set of places, $P = \{p_1, p_2, \ldots, p_m\}$, $m > 1$.
2. $T$: Set of transitions, $T = \{t_1, t_2, \ldots, t_n\}$, $n > 1$.
3. $F$: $(P \times T) \cup (T \times P)$: Input and output function of a net.
4. $W$: $(P \times T) \cup (T \times P) \rightarrow \mathbb{IN}$: Mapping function that assigns a weight to an arc, $W(p, t) > 0$ if $(p, t) \in F$, otherwise, $W(p, t) = 0$, all $p, t \in P \cup T$,
5. $M_o: P \rightarrow \mathbb{IN}$: Initial marking of a net, and the
6. $m_{o}$ is the initial tokens in place $p$.

A marked Petri net $N = (P, T, F, W, M_o)$ is called

1. an ordinary net if $W(p, t) = 1$, (p, t) $\in F$, p $\in P$, and $t \in T$.
2. a weighted net if $W(p, t) > 1$, (p, t) $\in F$, \exists p $\in P$, and $\exists t \in T$.
3. self-loop free if $W(p, t) > 0$ implies $W(t, p) = 0$ and $W(p, t) \in P \cup T$.
4. self-loop free if $W(t, p) > 0$ and $W(p, t) \in P \cup T$.

Assume that a node $a \in P \cup T$, the preset and postset of $a$ can be respectively represented as $\lambda = \{b \in P \cup T | \langle b, a \rangle \in F\}$ and $\lambda' = \{b \in P \cup T | \langle a, b \rangle \in F\}$. Incidence matrix $[N]$ of net $N$ is a $|P| \times |T|$ integer matrix with $[N](p, t) = W(t, p) - W(p, t)$. A transition $t \in T$ is enabled (can be fired) if $M(p) \geq W(p, t)$, \forall $p \in t$, denoted as $M(t)$, where $M(p)$ is the tokens number in place $p$. If a transition $t$ fires, it generates a marking $M'$, represented by $M(t)M'$, where $\forall p \in P$, $M'(p) = M(p) - W(p, t) + W(t, p)$. The set of net $N$ markings that are reachable from the initial marking $M_o$ is represented by $R(N, M_o)$. $R(N, M_o)$ is reached by a reachability graph,
designated as \( G(N, M_0) \), which is composed of arcs and nodes; arcs indicate transition firings labeled with \( t \), while nodes contain markings labeled with \( M_i \).

A marked Petri net \( N = (P, T, F, W, M_0) \) is
1. live if \( \forall t \in T, \exists t \) is live at \( M_0, \forall M \in R(N, M_0), \exists M \in R(N, M) \) such that \( M(t) = 0 \).
2. dead at \( M_i \) if \( t \in T \) such that \( M_0(t) \).

A \( P \)-vector is a column vector \( I: P \rightarrow Z \), which is indexed by \( P \), where \( Z = \{ \ldots, -2, -1, 0, 1, 2, \ldots \} \). If \( I \neq 0 \) and \( IT \) \( \forall t \in T, \exists t \) is live at \( M_0, \forall M \in R(N, M_0), \exists M \in R(N, M) \) such that \( M(t) = 0 \).

To ensure optimal supervision, the controlled system should include both dangerous and good markings; these are the legal markings indicated by \( M_L \). The legal markings for a PN system are stated as

\[
M_L = \{ M \mid M \in R(N, M_0) \land M_0 \in R(N, M) \}. \quad (1)
\]

A reachability graph is divided into two zones in [30], [31]: a live zone (LZ) and a deadlock zone (DZ), with the live zone containing all legal markings and the deadlock zone containing all illegal markings. An FBM is a specific illegal marking that can be created by firing one transition from the live zone to the deadlock zone. The FBM's are indicated by \( M_{FBM} \) and mathematically represented as

\[
M_{FBM} = \{ M \in DZ \mid \exists M' \in LZ, \exists t \in T, M'(t) = M \}. \quad (2)
\]

### B. ANALYSIS OF REACHABILITY GRAPH

Consider the reachability graph \( R(N, M_0) \) of a net \( N \). For purposes of deadlock control, markings in an \( R(N, M_0) \) can be categorized as good, bad, dangerous, and deadlock. A good marking is one that is capable of reaching both the initial and subsequent markings. A bad one has successors, but they cannot achieve the initial marking. A dangerous marking is capable of reaching the initial marking, but at least one of its successors cannot reach the initial marking. A deadlock implies a dead state in a system that has no successor. To ensure optimal supervision, the controlled system should include both dangerous and good markings; these are the legal markings indicated by \( M_L \). The legal markings for a PN system are stated as

\[
M_L = \{ M \mid M \in R(N, M_0) \land M_0 \in R(N, M) \}. \quad (1)
\]

The following constraint must be satisfied when there is a control requirement:

\[
\sum_{i=1}^{n} l_i \cdot M(p_i) \leq \beta \quad (3)
\]

where \( \beta \) and \( l_i \) are positive integer constants, and \( M(p_i) \) is the marking of the \( p_i \). Eq. (3) is transformed by the addition of a positive slack variable \( M(p_c) \) (the initial marking of a monitor \( p_c \)), and Eq. (3) becomes

\[
\sum_{i=1}^{n} l_i \cdot M(p_i) + M(p_c) = \beta. \quad (4)
\]

Eq. (4) defines a place invariant that must fulfill the equation \( I^*[N] = 0^T \). Therefore, the control place \( [N_c] \) can be stated as

\[
[N_c] = -L \cdot [N_p]. \quad (5)
\]

At the initial state, the initial marking \( M_0(p_c) \) of a monitor \( p_c \) can be formulated as

\[
M_0(p_c) = \beta - \sum_{i=1}^{n} l_i \cdot M_0(p_i). \quad (6)
\]

### D. OPTIMAL MONITOR FORMULATION

Suppose we have an AMS with a net \( (N, M_0) \) and its reachability graph \( R(N, M_0) \), which comprises of the \( M_L \) markings and the \( M_{FBM} \) markings. In this study, tokens in operation places (denoted as \( P_A \), \( P_A \in P \)) are only considered for the purpose of obtaining a PI to prevent an FBM, indicated as \( NA = \{ \forall p_c \in P_A \} \). To prevent an FBM \( M \in M_{FBM} \), the following constraint must be enforced:

\[
\sum_{i \in NA} l_i \cdot M(p_i) \leq \beta \quad (7)
\]

where

\[
\beta = \sum_{i \in NA} l_i \cdot M(p_i) - 1. \quad (8)
\]

The prohibited condition is denoted by Eq. (7). To ensure the maximally permissive control, after adding a monitor, all legal markings must be kept. To guarantee that no marking \( M' \in M_L \) can be prevented, coefficients \( l_i (i \in NA) \) should meet the reachability conditions

\[
\sum_{i \in NA} l_i \cdot M'(p_i) \leq \beta, \quad \forall M' \in M_L. \quad (9)
\]

By substituting the \( \beta \) in constraint (8) into constraint (9), the legal markings reachability conditions for an FBM can be formulated as

\[
\sum_{i \in NA} l_i \cdot (M'(p_i) - M(p_i)) \leq -1, \quad \forall M' \in M_L. \quad (10)
\]

For the coefficients \( l_i \)'s, solving constraint (10) generates a set of feasible solutions. Consequently, an optimal PI is calculated to guarantee that no FBM occurs and that all legal markings are reachable.
To decrease the number of legal markings $M_L$ and the number of FBM $M_{FBM}$, the study [8] introduces a vector covering method for the place invariant control, with the following details:

*Definition 1*: Let $(N, M_0)$ be a marked Petri net, $R(N, M_0)$ be its reachability markings, and two markings $M$ and $M'$ be in $R(N, M_0)$. If $M(p) \geq M'(p)$, $\forall p \in P_A$ that is represented by $M \geq_{A} M'$, then $M$ A-covers $M'$.

*Definition 2*: Let $(N, M_0)$ be a marked Petri net and $M^*_L$ be a subset of legal markings $M_L$ in $N$. If the following criteria are fulfilled, then $M^*_L$ is said to be a minimal covered set of $M_L$:

1. $\forall M \in M_L$, $\exists M' \in M^*_L$, subject to $M' \geq_{A} M$; and
2. $\forall M \in M^*_L$, $M' \in M^*_L$, subject to $M' \geq_{A} M$ and $M \neq M'$.

*Definition 3*: Let $(N, M_0)$ be a marked Petri net and $M^*_L$ be a subset of $M_{FBM}$ in $N$. If the following criteria are fulfilled, then $M^*_L$ is a minimal covered set of $M_{FBM}$:

1. $\forall M \in M_{FBM}$, $\exists M' \in M^*_L$, subject to $M' \geq_{A} M$; and
2. $\forall M \in M^*_L$, $M' \in M^*_L$, subject to $M' \geq_{A} M$ and $M \neq M'$.

$M^*_{FBM}$ and $M^*_L$ are respectively smaller than $M_{FBM}$ and $M_L$, when the vector covering method is used. There is no FBM that is reachable if PIs prevent all markings in $M^*_L$. Meanwhile, if $\forall M \in M^*_L$ are not prohibited by PIs, and then $\forall M \in M^*_L$ are kept. The optimal supervisor is calculated using the markings in the sets $M^*_L$ and $M^*_{FBM}$. As a result, for a marking $M \in M_{FBM}$, constraint (10) can be reformulated as

$$\sum_{i \in NA} l_i \cdot (M'(pi) - M(pi)) \leq -1, \quad \forall M' \in M^*_L.$$ (11)

**E. MONITOR FORMULATION FOR FORBIDDING FBMS**

This section describes how to construct a place invariant PI, which prohibits the maximum number of FBMs. We can develop a PI to prohibit a certain FBM using an approach described in Section II-D. Indeed, more FBMs may be prohibited by a PI. Next, we design a method to increase the number of FBMs, which a PI prohibits. Initially, we use the notations $N^*_I$, $N^*_{FBM}$, and $N^*_LM$ to indicate the number of FBMs, which a PI prohibits. Let $I_j$ be a PI for the constraint

$$\sum_{k \in NA} l_{jk} \cdot M_i(p_k) \leq \sum_{i \in NA} N^*_I, i \in N^*_{LM}, M_i \in M^*_L. \quad (12)$$

where $l_{jk}$’s are the coefficients of $I_j$, $I_j$ ($j \in N^*_I$) a set of binary variables, and $\beta_j$ is a positive integer variable. In constraint (12), if PI $I_j$ is selected to prohibit FBM, then $I_j = 1$; otherwise, $I_j = 0$.

$I_j$ prohibits the marking $M_i \in M^*_L$ if

$$\sum_{k \in NA} l_{jk} \cdot M_i(p_k) \leq \sum_{i \in NA} N^*_I, i \in N^*_{FBM}. \quad (13)$$

To represent the relationship between $I_j$ and $M_i$ in $M^*_L$, a set of binary variables $f_{jl}^{*}$ ($j,l \in N^*_I$) is introduced. Constraint (13) is modified as

$$\sum_{k \in NA} l_{jk} \cdot M_i(p_k) \forall j \in N^*_I, l \in N^*_{FBM}.$$ (15)

$$f_{jl} \leq I_j. \quad \forall j \in N^*_I, l \in N^*_{FBM} \quad (16)$$

Constraints (17) ensures that at least one FBM can be prohibited by one PI $I_j$ as

$$\sum_{l \in N^*_{FBM}} f_{jl} \geq 1 - I_j. \quad \forall j \in N^*_I \quad (17)$$

The objective function maximizes the set of FBMs which, a PI prohibits and can be formulated as

$$\text{Max } z= \sum_{j=1}^{N^*_I} \sum_{l=1}^{N^*_{FBM}} f_{jl}. \quad (18)$$

The coefficients of $I_j$ and $\beta_j$ must meet the conditions of reachability. Therefore, to design PI, the following ILPP is constructed, namely, an improved maximum number of for-bidding FBM problem (IMFFP).

**IMFFP:**

$$\text{Max } z= \sum_{j=1}^{N^*_I} \sum_{l=1}^{N^*_{FBM}} f_{jl}$$

subject to

$$\sum_{k \in NA} l_{jk} \cdot M_i(p_k) \leq \sum_{i \in NA} N^*_I, i \in N^*_{LM}, M_i \in M^*_L \quad (19)$$

$$\sum_{l \in N^*_{FBM}} f_{jl} \leq I_j. \quad \forall j \in N^*_I, l \in N^*_{FBM}, M_i \in M^*_L \quad (20)$$

$$\sum_{l \in N^*_{FBM}} f_{jl} \geq 1 - I_j. \quad \forall j \in N^*_I \quad (21)$$

$$f_{jl} \leq I_j. \quad \forall j \in N^*_I, l \in N^*_{FBM} \quad (22)$$

$$\sum_{l \in N^*_{FBM}} f_{jl} \geq 1 - I_j. \quad \forall j \in N^*_I \quad (23)$$

$$I_j = \{0, 1, 2, \ldots \} \quad \forall j \in N^*_I, k \in NA \quad (24)$$

$$f_{jl} = \{0, 1\} \quad \forall j \in N^*_I, l \in N^*_{FBM} \quad (25)$$

$$I_j = \{0, 1\} \quad \forall j \in N^*_I \quad (26)$$

$$\beta_j = \{0, 1, 2, \ldots \} \quad \forall j \in N^*_I \quad (27)$$
The IMFFP objective function $z$ is employed to solve the set of FBMs prohibited by PIs and to achieve a structurally minimal and behaviorally optimal supervisor, by ensuring that all markings in $M_L^*$ are reachable and the number of monitors is minimized.

**Theorem 1**: If $z = 0$, no FBM in $M_{FBM}^*$ has a maximally permissive PI.

**Proof**: Assume that there is a PI $I_j$ which can prohibit marking $M_l \in M_{FBM}^*$ by contradiction. Due to the permissive design of $I_j$, its coefficients $I_{l1}$, $I_{l2}$, ..., satisfy constraint (19). Given that $M_l$ is prohibited by $I_j$, we have $\sum_{k \in \mathcal{N}} b_{jk} \cdot M_l(p_k) \geq \beta_j I_l + 1$. Thus, $b_{jk} I_l = 1$ satisfies constraints (20-22). We have $z = \sum_{l \in \mathcal{N}_{FBM}} b_{jl} \geq 1$. $\forall j \notin N^*_f$. This contradicts $z = 0$. As a result, the conclusion is correct.

As known, it is NP-hard to solve an ILPP. The computational time required to solve an IMFFP is strongly influenced by the number of variables (denoted by $N_v$) and constraints (denoted by $N_c$) in it. Thus, we can discuss IMFFP in terms of its number of variables and constraints. The number of variables $\sum_{l \in \mathcal{N}_{FBM}} l (j \in N^*_f)$ and the number of constraints $\sum_{l \in \mathcal{N}_{FBM}} \sum_{l \in \mathcal{N}_{FBM}} b_{jl} I_l = 1$ to be calculated.

**Algorithm 1** A Deadlock Prevention Algorithm Based IMFFP

**Input**: A net $(N, M_0)$.

**Output**: A controlled net $(N_1, M_1)$.

1. Calculate the $M_L$ and the $M_{FBM}^*$.
2. Calculate the $M_L^*$ and the $M_{FBM}^*$.
3. VS: = $\emptyset$. $'^*$ The notation VS represents the monitors to be calculated.$'^*$
4. **for** all $M_{FBM}^*$ **do**
   i. Build the IMFFP;
   ii. Solve IMFFP: $\text{if } z \neq 0 \text{ then }$ $'^*$ Objective function.$'^*$
   Let $l'_{jk}$'s and $\beta_j$ be the solution;
   **else**
   Exit, because there is no solution;
   **end if**
   iii. Based on $I_j$, design a monitor $p_{c_i}$;
   iv. VS: = VS $\cup$ $[p_{c_i}]$. $'^*$ All $M_{FBM}^*$ is covered $'^*$
   **end for**
5. Insert all obtaining monitors in VS to the initial net $(N, M_0)$.
6. **Output** $(N_1, M_1)$.
7. **End**.

**III. DEADLOCK PREVENTION METHODS**

**A. DEADLOCK PREVENTION METHOD-BASED IMFFP**

In this section, we present a structurally minimal method and the deadlock prevention policy to prevent deadlocks by using IMFFP. The structurally minimal method is applied in one iteration to develop a set of maximally permissive monitors and minimize their number. The main advantage is that a few number of monitors are designed and it allows for the development of an optimal or nearly optimal supervisor. Algorithm 1 illustrates the deadlock prevention method based IMFFP.

Consider the FMS example in Figure 1 to demonstrate the proposed Algorithm 1. Figure 2 shows the system’s PN model. The model contains 20 reachable markings, 5 of which are FBMs markings $M_{FBM}^*$ and 15 of which are legal markings $M_L$. The minimal covered sets of FBMs $M_{FBM}^*$ and legal markings $M_L^*$ are $M_{FBM}^* = \{p_2 + p_5, p_3 + p_5, p_2 + p_6\}$ and $M_L^* = \{p_2 + p_3 + p_4, p_5 + p_6 + p_7\}$, respectively, when using a vector covering method.

Now, Algorithm 1 is considered, we introduce

1. three binary variables $I_1$, $I_2$, and $I_3$ to be computed.
2. nine binary variables $f_{11}, f_{12}, f_{13}, f_{21}, f_{22}, f_{23}, f_{31}, f_{32}$, and $f_{33}$ to indicate if $I_1$, $I_2$, and $I_3$ prohibit three FBMs in $M_{FBM}^*$.

Finally, we have IMFFP as follows

Max $z = f_{11} + f_{12} + f_{13} + f_{31} + f_{22} + f_{23} + f_{31} + f_{32} + f_{33}$ subject to

$\begin{align*}
&l_{15} + l_{16} + l_{17} \leq \beta_1 I_1 \\
&l_{12} + l_{13} + l_{14} \leq \beta_1 I_1 \\
&l_{25} + l_{26} + l_{27} \leq \beta_2 I_2 \\
&l_{22} + l_{23} + l_{24} \leq \beta_2 I_2 \\
&l_{35} + l_{36} + l_{37} \leq \beta_3 I_3 \\
&l_{32} + l_{33} + l_{34} \leq \beta_3 I_3 \\
&l_{13} + l_{15} \geq \beta_4 I_1 + 1 - H \cdot (1 - f_{11})
\end{align*}$

**FIGURE 1. FMS example and its process route.**
The above IMFFP is solved using the Lingo solver, and the optimal solution is \( l_{12} = 2, l_{15} = 1, l_{16} = 1, l_{11} = 1 \), \( \beta_1 = 2, f_{21} = 1, f_{13} = 1 \). Then, a monitor \( p_{c1} \) is developed for PI1: \( 2\mu_2 + \mu_5 + \mu_6 + \mu_{pc1} = 2 \). Thus, \( L_1 \) prohibits FBM2 and FBM3, and the preset transitions, postset transitions, and initial marking of the monitor \( p_{c1} \) are respectively \( p_{c1} = \{ t_2, t_6 \} \), \( p_{c1} = \{ t_1, t_5 \} \), and \( M_{1o}(p_{c1}) = \beta_1 = 2 \). In addition, \( l_{33} = 1, l_{35} = 1, l_{3} = 1, \beta_3 = 1, f_{31} = 1 \). Then, a monitor \( p_{c2} \) is developed for PI2: \( \mu_3 + \mu_5 + \mu_{pc2} = 1 \). Thus, \( L_3 \) forbids FBM1, and the preset transitions, postset transitions, and initial marking of the monitor \( p_{c2} \) are respectively \( p_{c2} = \{ t_3, t_6 \} \), \( p_{c2} = \{ t_2, t_5 \} \), and \( M_{1o}(p_{c2}) = \beta_3 = 1 \). All rest variables are equal zero.

Table 1 presents a summary of the results, with the first column indicating the calculated PI \( I_j \), the second column indicating the number of covered FBM in \( M^*_{FBM} \) that are prohibited by \( I_j \). The third to fifth columns indicate respectively the output transitions \( p_{cj} \), the input transitions \( p_{cji} \), and initial marking \( (M_{1o}(p_{cji})) \) of monitor \( p_{cji} \). The sixth and seventh columns indicate respectively the number of variables \( N_v \) and the number of constraints \( N_c \) in IMFFP. The last column indicating the required computational time (denoted by \( \Psi(s) \)) to solve the ILPP. Figure 3 illustrates the controlled system after adding two monitors to the initial net model.

### Table 1. Calculated monitors using Algorithm 1 for the model shown in Figure 2.

| PI | Covered | \( M^*_{FBM} \) | \( p_{c} \) | \( p_{cji} \) | \( M_{1o}(p_{cji}) \) | \( N_v \) | \( N_c \) | \( \Psi(s) \) |
|----|---------|-----------------|-------------|-------------|-----------------|--------|--------|--------|
| \( I_1 \) | \( 1 \) | \( 2, 6 \) | \( 2 \) | \( t_5, t_3 \) | \( t_3, t_5 \) | \( 1 \) | \( 33 \) | \( 30 \) | \( < 2 \) |
| \( I_2 \) | \( 1 \) | \( 2, 6 \) | \( 2 \) | \( t_5, t_3 \) | \( t_3, t_5 \) | \( 1 \) | \( 33 \) | \( 30 \) | \( < 2 \) |

### B. Deadlock Prevention Method - Based Colored Petri Nets

A colored Petri net (CPN) is represented by \( N = (P, T, C, F, K, M_0) \), where

1. \( P \) and \( T \) are defined in Section 2.1;
2. \( C(p) \) and \( C(t) \) are respectively represent the sets of colors connected with \( p \in P \) and \( t \in T \). We let \( C(p) = \{ a_{i1}, a_{i2}, \ldots, a_{il} \} \) and \( C(t) = \{ b_{j1}, b_{j2}, \ldots, b_{jT} \} \) where \( u_i = |C(p_i)| \) and \( v_j = |C(t_j)| \);
3. \( F: I(p, t) \cup O(p, t) \): Input and output function of a net, where the input function is expressed as \( I(p, t): C(p) \times C(t) \rightarrow \mathbb{N} \), and the output function is expressed as \( O(p, t): C(p) \times C(t) \rightarrow \mathbb{N} \).
4. $K: P \rightarrow IN$: represents the function of capacity that assigns the maximal number of tokens to each place $K(p_i)$.

5. $M_o: P \rightarrow IN$ is a marking function that allocates tokens to the places. $M_o(p_i)$ denotes the initial number of tokens in $p_i$, regardless of their color, while $M_o(p_i, a_{ij})$ denotes the initial tokens in $p_i$, which have the color $a_{ij}$.

The enabling and firing rules of the transition $t_j$ in a colored Petri net can be stated as below.

1. A transition $t_j$ is said to be a process-resource-enabled if

   $M(p_i, a_{ih}) \geq I(p_i, t_j)(a_{ih}, b_{jk})$, $\forall p_i \in P$, $\forall p_i \in t_j, a_{ih} \in C(p_i), b_{jk} \in C(t_j)$  \hspace{1cm} (28)

   and

   $K(p_i) \geq M(p_i, a_{ih}) + O(p_i, t_j)(a_{ih}, b_{jk})$

   $-I(p_i, t_j)(a_{ih}, b_{jk})$, $\forall p_i \in P$, $\forall p_i \in t_j, a_{ih} \in C(p_i), b_{jk} \in C(t_j)$.  \hspace{1cm} (29)

Definition 4: Let $(N, M_o)$ be a marked Petri net. The deadlock supervisor for $(N, M_o)$ designed in IMFFF is represented as $(V, M_{Vo}) = (P_V, T_V, F_V, M_{Vo})$. Here, $(V, M_{Vo})$ can be replaced by a common colored subnet that is a net with $N_{DC} = \{p_{global}\}, \{T_{DCi} \cup T_{DCo}\}, F_{DC}, C_{DC}, M_{DCo}$, where $p_{global}$ is named the combined monitor of all control places $P_v = \{p_i | p_i \in VS\}, VS = \{p_{c1}, p_{c2}, ..., p_{cj}\}$. $T_{DCi} = \cup_{i \in VS} f_t(i \in p_i)$. $T_{DCo} = \cup_{i \in VS} f_t(i \in p_i)$. $F_{DC} \subseteq (p_{global}) \times (T_{DCi} \cup T_{DCo}) \cup (T_{DCi} \cup T_{DCo}) \times (p_{global})$ is the set of arrows, which connect the combined monitor with transitions (and vice versa). $C_{DC} = \cup_{i \in VS} C_{pci(i)}$ is the set of all monitors color, where $C_{pci(i)}$ is the color of the monitor $p_{ci}$ that maps $p_{global}$ into colors. $(N_{DC}, M_{DCo})$ is named a common colored subnet. For all $p_i \in P_V, M_{DCo}(p_{global}) = \sum_{i \in VS} M_{Vo}(p_i)$, where $M_{DCo}(p_{global})$ is an initial tokens with the colors of the combined control place.

Definition 5: Let $(N, M_o)$ be a marked Petri net and $(N_{DC}, M_{DCo})$ be a common colored deadlock control subnet with $N_{DC} = \{p_{global}\}, \{T_{DCi} \cup T_{DCo}\}, F_{DC}, C_{DC}, M_{DCo}$. We call $(N_{CN}, M_{CNo})$ a controlled colored Petri net. Furthermore, $(N_{CN}, M_{CNo}) = (N, M_o) \parallel (N_{DC}, M_{DCo})$, which is the integration of $(N, M_o)$ and $(N_{DC}, M_{DCo})$, where $N_{CN} = (P \cup \{p_{global}\}, T \cup T_{DCi} \cup T_{DCo}, F \cup F_{DC}, C_{DC}, M_{CNo})$, and $R(N_{CN}, M_{CNo})$ be its reachable graph. Algorithm 2 illustrates the deadlock prevention method by using IMFFF and CPN. Reconsider the controlled net in Figure 3 to demonstrate the proposed Algorithm 2. Figure 4 depicts the $p_{global}$ place of all control places $P_v$ in Figure 3, as generated by Algorithm 2. The output arcs of $p_{global}$ that obtained from Algorithm 1 are represented as $p_{c1} = \{t_1, t_5\}$ and $p_{c2} = \{t_2, t_5\}$. Therefore, $T_{DCo}$ can be represented as $T_{DCo} = \{t_1, t_2, t_5\}$, as depicted in Figure 5. The input arcs of $p_{global}$ that obtained from Algorithm 1 are represented as $p_{c1} = \{t_2, t_7\}$ and $p_{c2} = \{t_3, t_6\}$. Thus, $T_{DCi}$ be stated as $T_{DCi} = \{t_2, t_3, t_6, t_7\}$, as displayed in Figure 6. In addition, $M_{DCo}(p_{global}) = \sum M_{Vo}(V_S) = M_{Vo}(p_{c1}) + M_{Vo}(p_{c2}) = 2 + 1 = 3$. Petri net model in Figure 3 contains two color types: $C_{DC} = \{C_{p1, c2}\}$. Accordingly, as shown in Figure 7, the $p_{global}$ has three colored tokens: two tokens with color $C_{p1, c2}$ and one token with color $C_{p2}$. Finally, the controlled colored Petri net $(N_{CN}, M_{CNo})$ of the net shown in Figure 3 using Algorithm 2 is presented in Figure 8.

Algorithm 2 Deadlock Prevention Method Based IMFFF and CPN

Input: A net $(N_1, M_1)$. By using Algorithm 1.*/

Output: A net $(N_{CN}, M_{CNo})$.

1. Merge all monitors $P_v$ into a single monitor ($p_{global}$), considering the procedures below:
   a. Design the output arcs $T_{DCo}$, then connect them with $p_{global}$; /* By Definition 4*/
   b. Design the input arcs $T_{DCi}$, then connect them with $p_{global}$; /* By Definition 4*/
   c. Define colors $C_{pci}$ for a monitor $p_{global}$; /* By Definition 4*/
   d. Calculate the initial tokens with colors $M_{DCo}(p_{global}) = \sum M_{Vo}(V_S)$. /* By Definition 4*/

2. Add the $p_{global}$ into the net $(N_1, M_1)$.

3. Output $(N_{CN}, M_{CNo})$.

4. End
TABLE 2. Calculated monitors using Algorithms 1 for the net shown in Figure 9.

| PI | Covered $M'_{FBM}$ | $p_{cl}$ | $t_{p_{cl}}$ | $M_{id}(p_{cl})$ | $N_v$ | $N_c$ | $\mathcal{P}(s)$ |
|----|---------------------|---------|-------------|-----------------|------|------|----------------|
| $I_1$ | 3 | $t_1, t_2, t_4$ | $3t_5$ | 2$t_7, 3t_7$ | 9 | 168 | 352 | < 152 |
| $I_2$ | 5 | $4t_1, 4t_2, t_4$ | $3t_5, 5t_6$ | $t_9, 7t_{13}$ | 14 | |

TABLE 3. Comparison of Algorithms 1 and 2 performance with some deadlock prevention methods for the net shown in Figure 9.

| Parameters | [37] | [38] | [39] | [8] | [21] | Algorithm 1 | Algorithm 2 |
|------------|------|------|------|-----|------|-------------|-------------|
| No. states | 205  | 205  | 205  | 205 | 205  | 205         | 205         |
| No. control places | 6    | 9    | 5    | 8   | 2    | 2           | 1           |
| No. arcs | 32   | 42   | 23   | 37  | 15   | 15          | 10          |
| Permissiveness (%) | 100  | 100  | 100  | 100 | 100  | 100         | 100         |

Control places by Algorithm 1

Control places by Algorithm 1

Control places by Algorithm 1

Control places by Algorithm 1

Point using the GPenSIM tool [33]–[36]. Figure 9 illustrates a Petri net model, which has been studied in [8], [10], [21], [28], [37]–[40]. It consists of 19 places and 14 transitions. The model has 282 reachable states with 205 legal markings and 54 FBMs. The minimal covered sets of legal markings $M^*_L$ and FBMs $M^*_FBM$ are respectively 26 and 8 markings. The implementations of Algorithm 1 are summarized in Table 2. Next, the two resulting monitors using Algorithm 1 are combined to form $p_{global}$ using Algorithm 2. The output arcs of $p_{global}$ are represented as $T_{DCO} = \{t_1, 5t_2, 2t_4, 4t_9, 7t_{13}\}$. The input arcs of $p_{global}$ are represented as $T_{DCI} = \{3t_5, 5t_6, 3t_7, 12t_{13}\}$. In addition, $M_{DCO}(p_{global}) = \sum M_{id}(V_S) = M_{id}(p_{c1}) + M_{id}(p_{c2}) = 9 + 14 = 23$. Thus, we have two color types: $C_{DC} = \{C_{pc1}, C_{pc2}\}$. The $p_{global}$ place has 23 colored tokens: 9 tokens with the color $C_{pc1}$ and 14 tokens with the color $C_{pc2}$. Table 3 shows the comparison the Algorithms 1 and 2 to other existing deadlock control methods in terms of the numbers of added monitors, added arcs, and states of the controlled net. Algorithm 2 yields a supervisor with one monitor and 10 arcs, both of which are minimal in comparison to other methods in [8], [21], [37]–[39].

Next, Figure 10 illustrates a Petri net model, which has been studied in [41], [44], [45]. It consists of 26 places...
and 20 transitions. The model has 26750 reachable states with 21581 legal markings and 4211 FBMs. The minimal covered sets of legal markings $M^*_{L}$ and FBMs $M^*_{FBM}$ are respectively 393 and 3 markings. Table 4 illustrates the computed monitors for the model presented in Figure 10 using Algorithm 1. Then, the six resulting control places using Algorithm 1 are combined to form $p_{global}$ using Algorithm 2. The output arcs of $p_{global}$ are represented

FIGURE 9. A net ($N, M_0$) of the first FMS.

FIGURE 10. A net ($N, M_0$) of the second FMS presented in Ezpeleta et al. [41].
TABLE 4. Calculated monitors using Algorithm 1 for the net shown in Figure 10.

| PI | Covered $M^*$ \text{FBM} | $p_{c1}$ | $p_{c2}$ | $M_{10}(p_{c2})$ | $N_v$ | $N_c$ | $\mathcal{V}(s)$ |
|----|-----------------|--------|--------|-----------------|-----|-----|--------|
| $I_1$ | 8 | $t_5, 27t_7, t_11, 6t_{15}$ | $t_5, 24t_{18}, 3t_{10}, t_{13}$ | 71 |
| $I_2$ | 19 | $3t_{16}, 9t_{17}$ | $18t_{18}$ | 196 |
| $I_3$ | 3 | $6t_{16}, t_{4}, t_{18}, 4t_{17}, t_{18}$ | $6t_{16}, t_5, 5t_{16}, t_6$ | 34 |
| $I_4$ | 1 | $t_6, t_{16}$ | $t_9, t_{17}$ | 2 |
| $I_5$ | 1 | $t_6, t_{15}$ | $t_{10}, t_{16}$ | 2 |
| $I_6$ | 2 | $t_5, t_{11}$ | $t_{10}, t_{13}$ | 2 |

Having computed $M_{10}(p_{c2})$, the system is deadlock-free. This follows from the fact that $M_{10}(p_{c2}) = 71$, which implies that $M_{10}(p_{c2}) + 2 = 73 > 2$, and hence $M_{10}(p_{c2})$ is not a global place.

as $T_{DC0} = \{9t_1, 16t_3, t_4, 27t_7, 45t_{18}, 9t_9, 2t_{11}, 48t_{15}, t_{16}, 13t_{17}, 46t_{18}\}$. The input arcs of $p_{global}$ are represented as $T_{DC} = \{6t_3, t_4, 18t_5, 29t_8, 2t_9, 54t_{10}, 17t_{13}, t_{16}, 50t_{17}, 18t_{18}, 8t_{19}\}$. In addition, $M_{DC}(p_{global}) = \sum M_{10}(V_S) + M_{10}(p_{c1}) + M_{10}(p_{c2}) + M_{10}(p_{c3}) + M_{10}(p_{c4}) + M_{10}(p_{c5}) + M_{10}(p_{c6}) = 71 + 34 + 2 + 2 + 2 = 341$. Thus, we have six color types: $C_{DC} = \{C_{pc1}, C_{pc2}, C_{pc3}, C_{pc4}, C_{pc5}, C_{pc6}\}$. The $p_{global}$ place has 341 colored tokens: 71 tokens with color $C_{pc1}$, 196 tokens with the color $C_{pc2}$, 34 tokens with the color $C_{pc3}$, 2 tokens with the color $C_{pc4}$, 2 tokens with the color $C_{pc5}$, and 2 tokens with the color $C_{pc6}$. Finally, the comparison of the Algorithms 1 and 2 performance with some deadlock prevention methods for the net shown in Figure 10 is shown in Table 5. Algorithm 2 provides a controller with one control place and 22 arcs, both of which are minimal in comparison to other methods in [8], [21], [30], [39], [41]–[43].

V. CONCLUSION

This paper presents an approach for preventing deadlocks based on colored Petri nets and a structurally minimal method. First, a vector covering technique is applied to calculate a minimal covered set of FBMs and legal markings. By solving an ILPP in one iteration, place invariants corresponding to control places are constructed to prohibit the maximum number of FBMs. The first-step-obtained controlled model makes the Petri net supervisor significantly more complicated. In the second step, colored Petri nets are applied to design the smallest number of monitors by integrating all generated control places into a single global control place. In comparison to previous work [8], [21], [30], [37]–[39], [41]–[43], our approach enables the development of an optimal or near-optimal supervisor with fewer monitors and without the need for iterations to design place invariants to prohibit the FBMs, while there are no prohibited legal markings.

The main disadvantage of the developed approach is that it is subject to modifications in control requirements and specifications, such as adding new equipment and products or modifying the system’s processing routes. In the case that these problems appear, the system must be changed. The proposed model may thus be subject to new deadlock problems. Therefore, our future study will focus on optimizing the efficiency of the proposed method for valid and quick reconfiguration of the FMS [46] and the fault and its security issues [47], [48].

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TABLE 5. Comparison of Algorithms 1 and 2 performance with some deadlock prevention methods for the net shown in Figure 10.

| Parameters | [41] | [42] | [43] | [30] | [39] | [8] | [21] | Algorithm 1 | Algorithm 2 |
|------------|-----|-----|-----|-----|-----|-----|-----|----------|----------|
| No. states | 6287 | 6287 | 12656 | 21562 | 21581 | 21581 | 21581 | 21581 | 21581 |
| No. control places | 18 | 6 | 16 | 19 | 13 | 17 | 6 | 6 | 1 |
| No. arcs | 106 | 32 | 88 | 112 | 82 | 101 | 45 | 45 | 22 |
| Permissiveness (%) | 29.13 | 29.13 | 58.64 | 99.91 | 100 | 100 | 100 | 100 | 100 |

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HUSAM KAID received the B.S. degree in industrial engineering from the University of Taiz, Taiz, Yemen, in 2010, and the M.S. and Ph.D. degrees in industrial engineering from King Saud University, Saudi Arabia, in 2015 and 2021, respectively. He is currently a Researcher at the Industrial Engineering Department, College of Engineering, King Saud University. His research interests include design and analysis of manufacturing systems, deadlock control in manufacturing systems, supply chain simulation, operations research, optimization techniques, and bibliometric network analysis.
ABDULRAHMAN AL-AHMARI received the Ph.D. degree in manufacturing systems engineering from The University of Sheffield, Sheffield, U.K., in 1998. He has worked as the Dean of the Advanced Manufacturing Institute, the Chairman of the Industrial Engineering Department, and led a number of funded projects from different organizations in Saudi Arabia. He is currently a Professor of industrial engineering with King Saud University, Riyadh, Saudi Arabia. He has published papers in leading Journal of Industrial and Manufacturing Engineering. His current research interests include advanced manufacturing technologies, Petri nets, analysis and design of manufacturing systems, computer integrated manufacturing, optimization of manufacturing operations, flexible manufacturing systems and cellular manufacturing systems, and applications of decision support systems in manufacturing.

ZHIWU LI (Fellow, IEEE) received the B.S. degree in mechanical engineering, the M.S. degree in automatic control, and the Ph.D. degree in manufacturing engineering from Xidian University, Xi’an, China, in 1989, 1992, and 1995, respectively. He joined Xidian University in 1992. Over the past decade, he was a Visiting Professor at the University of Toronto, Technion (Israel Institute of Technology), Martin-Luther University, Conservatoire National des Arts et Métiers (CNAM), Meliksah Universitesi, the University of Cagliari, the University of Alberta, and King Saud University. He is currently with the Macau University of Science and Technology. His current research interests include Petri net theory and application, supervisory control of discrete event systems, workflow modeling and analysis, system reconfiguration, game theory, and data and process mining. He is listed in Marquis Who’s Who in the World, 27th Edition, in 2010. He was a recipient of an Alexander von Humboldt Research Grant, Alexander von Humboldt Foundation, Germany, and Research in Paris, France. He is the Founding Chair of Xi’an Chapter of IEEE Systems, Man, and Cybernetics Society. He serves as a reviewer for more than 90 international journals.

WADEA AMEEN received the M.Sc. and Ph.D. degrees from King Saud University, Saudi Arabia. He is currently an Assistant Professor with the Faculty of Engineering and Architecture, Industrial Engineering Department, Al-Yamamah University, Saudi Arabia. His research interests include additive manufacturing; CAD/CAM; product design analysis, and design of manufacturing systems; and optimization of manufacturing processes.

* * *

WADEA AMEEN received the M.Sc. and Ph.D. degrees from King Saud University, Saudi Arabia. He is currently an Assistant Professor with the Faculty of Engineering and Architecture, Industrial Engineering Department, Al-Yamamah University, Saudi Arabia. His research interests include additive manufacturing; CAD/CAM; product design analysis, and design of manufacturing systems; and optimization of manufacturing processes.

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