A Colored Petri Nets Model for the Diagnosis of semantic faults of BPEL Services

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Abstract. The paper contributes to modeling an orchestrated complex Web Service (BPEL) with Colored Petri Nets (CPNs) for diagnosis. In the CPNs model, colored tokens are used to represent the faults (either in inputs data or external faulty Web services) in a BPEL process. Three I/O data dependency relations are introduced into the color functions of the CPN models. Thus the transmitting of faults between the process control and internal data, data and data, in a BPEL service can be modeled as the execution of a CPN system. We give a concrete translation from a BPEL service to a CPNs model and define a model-based diagnosis framework. Based on the marking evolution equation in Petri nets theory, we construct an inequations system as a diagnosis problem and solve it with an algebra algorithm. 1

Key words: Model-based diagnosis, Web service, BPEL, Colored Petri Nets

1 Introduction

Self-healing software is one of the important challenges for Information Society Technologies research. Our paper proposes a centralized diagnosis approach for BPEL ([11]) services, whose goal is to design a framework for self-healing Web services by adopting artificial intelligence methodologies to solve the diagnosis problem by supporting online detection and identification of faults.

A Web service (WS) is a set of distributed message oriented interacting components. We can construct complex WS systems by composing basic WSs in two ways: orchestration and choreography (P2P). An orchestrated BPEL service is a central process to organize (basic or complex) WSs to finish complex tasks. A choreographed WS has not a central process while all the involved WSs are aware of their partners but none has the global view of the whole WS application.

1 This research has been initiated in the framework of the FP6 IST project 516933, WSDIAMOND (Web Services DIAgnosability, MONitoring and Diagnosis) and continued in the framework of the national ANR project WEBMOV (Web services Modeling and Verification).
Distributed WS applications make B2B engineering more convenient but raise more challenges for handling dysfunctions. For example, how to locate the source and reason of faults when they occur somewhere in a distributed WS application? As orchestration is the basic of the WS composition, we focus on single BPEL service diagnosis based on CPN ([7]) model which can be easily extended to a distributed environment.

During the interaction of distributed WS components, subtle faults can come from corrupted data or some functional errors. Due to the message oriented nature of WS applications, faulty data is propagated through the execution trace and is used to elaborate other faulty data and control decisions. In this way the subtle faults become large ones.

Consider the following example which will be used as an illustration example along this paper: a BPEL service FlightAgent calculates a series of business flight costs. The FlightAgent starts with a receive activity $C$ to receive a request string of the series of departure cities and dates, for example, from Paris to London on 01/03/2008, and from London to Madrid on 03/03/2008, from Madrid to Rome on 05/03/2008, and from Rome to Paris on 09/03/2008, all the dates are in French format. FlightAgent iteratively (by using While activity $W$) invokes an invoke activity $S$ to split the request string to get the information for one flight: the departure city, a departure date, and an arriving city (which is also the departure city of next flight). Whereafter an invoke activity $O$ reserves the flight tickets and cumulatively calculates the flight fees.

We consider two types of faults: the faulty input data and the bad basic WS which sometimes cannot be tested or detected immediately. For example, bad activity $S$ interprets the date format incorrectly as to different date formats in English and French, 01/03/2008, 03/03/2008, 05/03/2008, and 09/03/2008 are misinterpreted as January 03, 2008, March 03, 2008, May 03, 2008, and September 03, 2008, which is hard to test locally. As to the prizing rules of the airline, at the end of the process, reply activity $P$ returns the total ticket price of the whole trip (in figure 3a) which is unreasonably huge. The client (or other Web service which invokes FlightAgent) can arise an exception. These two types of faults both reflect on data within the BPEL process. So we consider both of them as data fault while the latter one is explained as the basic WS fault. Note that we suppose the overall orchestration and choreography schema is correctly designed.

In this paper, we address the data faults by using the model based diagnosis approach, and more specially, the discrete event model based approach ([1], [2], [3], [4], [10], [15], [16], [18]). Among the usual discrete event model, we use colored Petri nets to define the diagnoser. Many works use the Petri nets to do diagnosis ([2], [10], [12], [15], [16]). Some works use high level Petri nets to modeling WS ([4], [17], [18], [3]) as they are more expressive from the aspect of data evolution. While there are few CPN model focus on diagnosis problem.

The main originality of this work is a natural use of the colored Petri nets (supported by CPN Tools [6]); the color domain is used to model data (states) status and transitions are used to define transition status. The model presented
here can be generalized to a very large software domain besides Web services. Another originality is the diagnosis methods: unlike most of other works based on Petri nets, we don’t use an unfolding approach ([2], [12], [15], [16]), but use the incidence matrix and the characteristic vector of the observed trace in order to transform the diagnosis problem to an inequations system, and then we propose an algorithm to solve one inequation and then the inequations system.

The paper is organized as follows: in section 2, we introduce CPN model for the BPEL services and define their firing rules. We define CPN model for typical basic activities and structural operators of BPEL in section 3; in section 4, we define the diagnosis problem and its solution and illustrate it with a concrete example; in section 5, we introduce some related work, compare the different methods, and give some directions for future research.

2 Colored Petri Net

A Petri net is a Colored Petri Net if its tokens can be distinguished by colors. Here we restrict the definition of Colored Petri Net that we use in this paper.

Let $E$ be a set, a multiset on $E$ is an application $m$ from $E$ to $\mathbb{Z}$ (a multiset is denoted as $m = q_0 e_0 + ... + q_n e_n$ where $q_i = m(e_i)$, $\mathbb{Z}$ is the integer set). We use $\mathcal{M}(E)$ to define the set of finite multisets from $E$ to $\mathbb{Z}$, and $\mathcal{M}^+(E)$ if we restrict it to $\mathbb{N}$. Sum and subtract operators between two multisets are defined as in [9]. For two given value domains $D$, $D'$, we denote by $[D \rightarrow D']$ the set of possible functions from $D$ to $D'$.

**Definition 1** A Colored Petri Net graph (CPN graph) is a tuple $N = (\Sigma, X, F, P, T, cd, Pre, Post)$, where: $\Sigma$ is a set of colors (see [9]), $X$ is set of variables that range over $\Sigma$, $F$ is a set of color functions, $F \subseteq \bigcup_n [\Sigma^n \rightarrow \Sigma]$. $P$ is a set of labeled places, and there are two types of places exists: $AP$, the activation places which contains the CPN execution control, $DP$, which contains the data used during the execution of CPN, especially, we denote the constant data places set as $CP$; Formally, this is represented as follows: $P : AP \cup DP$ and $CP \subseteq DP$, $AP \cap DP = \emptyset$. $T$ is a set of labeled transitions, we denote Type : $T' \rightarrow T''$ with $T', T'' \subseteq T$ and $T' \cap T'' = \emptyset$ is a type function of $T$, $Cd : P \rightarrow 2^\Sigma$, is a function that associates to each place a color domain\(^2\). $Pre, Post$ are forward and backward matrices such that $Pre : P \times T \rightarrow \mathcal{M}^+ (\Sigma \cup X)$, are input arc expressions. And $Post : P \times T \rightarrow \mathcal{M}^+ (E)$, are output arc expressions[9].

\(\mathcal{E}\) represents a color expression which can be a color constant, a variable, or a color function of $F$ (completely or partially instantiated). Given an expression $e \in \mathcal{E}$, we use $Var(e)$ to denote the set of variables which appear in $e$, and $Eval(e)$, the evaluation of $e$ in $\Sigma$.

We denote $t$ and $t'$ as the input and output places set of transition $t$, $p$ and $p'$ as the input and output transitions set of place $p$.

\(^2\) In this definition, a transition has no color domain. This restriction will be explained in section 3.2.
Definition 2 A CPN graph \( N = (\Sigma, X, P, T, cd, Pre, Post) \) is well formed iff:
\[\forall t \in T, \forall p \in X, \text{ we have } \text{Var}(Post(p, t)) \subseteq \text{Var}(Pre(., t)) \]
\[= \bigcup_{p' \in X} \text{Var}(Pre(p', t)).\]

In a well-formed CPN graph, we restrict that for each transition, the output arc expressions must be composed by the variables which are in the input arcs expressions.

To each CPN graph, we associate its terms incidence Matrix \( C (P \times T \rightarrow M(\mathbb{E})) \) with \( C = Post - Pre \).

In the following, we define the behaviors (the dynamics) of a CPN System.

Definition 3 A marking \( M \) of a CPN graph is a multiset vector indexed by \( P \), where \( \forall p \in P, M(p) \in M^+(cd(p)) \).

Operators + and − on multisets are extended to markings in an obvious way.

Definition 4 A Colored Petri Net system (CPN system) is a pair \( S = (N, M_0) \) where \( N \) is a CPN graph and \( M_0 \) is an initial marking.

Definition 5 A transition \( t \) is enabled in a CPN system \( S \) with present marking \( M \), iff \( \exists u, \text{ with } M \geq Pre(., t)^u, \text{Var}(Pre(., t)) \rightarrow \Sigma, \text{ which is a binding of the input arcs variables.} \)

We use \( M[t]^u \) to denote that \( t \) is enabled in \( M \) by the use of \( u \), and we use the classic notation \( M[t] \) if \( u \) is not important (e.g. when \( u \) is unique).

Definition 6 Let \( M \) be a marking and \( t \) a transition, with \( M[t]^u \) for some \( u \). The firing of the transition \( t \) changes the marking of CPN from \( M \) to \( M' = M + C(., t)^u \). We note the firing as \( M[t]^u M' \).

Definition 7 We extend the definition 6 to a sequence of transitions \( \delta \in T^* \) as:
\( M[\delta]M \) if \( \delta \) is the empty sequence; \( M[wt]M' \) iff \( \exists M'' \) such that \( M[w]M'' \) and \( M''[t]^u M' \).

3 From BPEL to CPN model

There exist already many works dedicated to translate BPEL services into CPN model for verifying ([3], [13]), composing ([18]), supervising ([4]), etc.. In this section, we construct our own CPN model by introducing the faulty behaviors into Petri nets model which is suitable not only for diagnosing BPEL services, but also for diagnosing other large software systems.

A BPEL process consists of basic activities and structured operators. The idea of modeling BPEL to CPN is: to map each primitive data to a place, each basic activity to a transition. To each basic activity, input and output activation
places $a^{in} \in P$ and $a^{out} \in P$ are associated to identify the execution order. To include the fault model, additional transitions are added to represent the unobservable faulty activities either in basic WSs or in composite BPEL services. The structured operators are modeled as CPNs which sew the structured sub-processes by combining, disjointing, or generating the local activation places $a^{in}_i \in P$ and $a^{out}_i \in P$. Once a red token is generated by a faulty transition in a basic activity, the fault is passed along the execution trace through the arc expressions which are represented in $Pre$ and $Post$ matrices. In the following, we define how to translate the static and dynamic features into CPN models.

3.1 BPEL data Variables and constants

BPEL data variables and constants
To catch maximally the dependency between data (variables, constants, etc.), we decompose the structured data types into their elementary parts, denoted by the leaves of their XML tree structure. For a variable $X$ of type $m$ (resp. an Xpath expression), we use $x_i$ to range over the $Leaves(m)$ (resp. $Leaves(X)$) and denote the $x_i$ part of $X$ by a couple $(X, x_i)$. In our mapping, each data variable and constant is represented by a unique place in CPNs.

Color Domain
In our CPN model, three colors are used: red ($r$) marks a place with faulty data value; black ($b$), not faulty data value; and unknown color ($*$), unknown correctness of data value.

Data dependency within BPEL v.s. color functions
To specify the effect of each activity on data, we give each activity a data dependency signature in term of three dependency relations ([1]): forward ($FW$), if the activity just copies the value from the input to the output; source ($SRC$), if the output data is generated by the activity; and elaboration ($EL$), if the output data is elaborated from the set of input data. To each of this dependency relation, we associate a color propagation function to represent the data status (faulty, correct, or unknown status) production.

Definition 8 Given the data relations set $D = \{FW, SRC, EL\}$, $\forall d \in D$, the associated color propagation function $d^c$ is defined as: $\forall c, c' \in \Sigma, \forall C \subseteq \Sigma$,

$$
\begin{align*}
FW^c & \in [\Sigma \rightarrow \Sigma], \quad FW^c(c) = c \\
SRC^c & \in [\emptyset \rightarrow \Sigma], \quad SRC^c = * \\
EL^c & \in [2^\Sigma \rightarrow \Sigma], \quad EL^c(C) = c', \quad \text{with } c' = \begin{cases} b, & \text{iff } \forall c \in C, \ c = b \\
r, & \text{iff } \exists c \in C, \ c = r \\
*, & \text{iff } \exists c \in C, \ c = * \land \not\exists c'' \in C, \ c'' = r 
\end{cases}
\end{align*}
$$

In the following sections, we model dynamic features, the basic BPEL activities and structured operators with CPNs.

3.2 Translate basic BPEL activities into CPNs

BPEL service is composed with a series of basic activities. We map each basic activity to its CPN model. Due to space limitation, we restrict our definitions to
four main basic activities (Receive, Assign, Invoke, and Reply) while the other similar activities can be easily translated in the same way.

The main idea in mapping BPEL basic activities to CPNs is: each primitive data is mapped to a place, each basic activity is mapped to a transition, and Pre and Post matrices are defined based on data dependency. In order to distinguish the activities execution order and the traces among different branches, to each basic activity, we associate an input activation place $a^{in}$ and an output activation place $a^{out}$.

As we focus on the data fault diagnosis of one BPEL service, the BPEL service code is assumed to be correct. Possible faults can be faulty data received by Receive activities, or faulty activities which come from other WS called by Invoke activities. So we must introduce fault models for Receive and Invoke activities to localize the faulty data or external WS. Our approach is to introduce additional transitions to represent the unobservable faulty activities and to define the color functions in Pre and Post matrices which represent the propagation of faults.

![Fig. 1. CPN models of basic activities](image)

**Receive($m,X$):** an activity simply copies the values from a message $m$ to a local variable $X$. In order to model the receiving of a set of faulty parts from a message value, we add for each part of the message an internal transition (fault) before the firing of the receive transition in figure 1(a). Note that data places $(m,m_i), (x,x_i)$ are simplified as $m_i, x_i$.

The CPN model of Receive contains two kinds of fault transitions: the activation fault transition $t_{fa}$, and the fault transitions $t_f$, we define their types as: $Type(t_{fa})=Type(t_f)=t_{rec}$. The execution of $t_f$ is triggered by the consumption of the token in the input activation place. Once $t_{fa}$ (or $t_f$) is executed, we can deduce that there is a faulty control (or data) input. The transmission of the fault (red token) is illustrated on the arc expressions. Each arc expression
represents the colored token consumed (on an arc \((p, t)\)) or produced (on an arc \((t, p)\)). To keep the liveness of the CPNs, we add an arc from the output place \(x_i\) to the receive transition \(t_{rec}\) and its associated color function \(C_{x_i}\) is the color of the output data place \(x_i\).

**Reply\((Y, m)\):** an activity that copies values from a variable \(Y\) to a message \(m\) for returning the response of the BPEL service to its invoker. So \(Reply\) can be the ending of BPEL and simply forwards (FW) values. There is no fault model in its CPN and we simply fill \(Post\) with FW functions.

**Assign\((X, Y)\):** an activity that reorganizes local variable parts inside a BPEL process without changing the values. So its model is similar to \(Reply\) activity. Similar operators: \(Throw\) and \(Rethrow\). The \(Wait\), \(Empty\), and \(Exit\) activities do not have relation with the variables, so their CPN model only have the input and output activation places.

**Invoke\((X, Y)\):** an activity that calls another basic or composite Web service. It takes the value of the variable \(X\) as input and stores the output in the variable \(Y\). The data dependency can be \(FW\), \(EL\), and/or \(SRC\). As \(Y\) can be infected by external faulty WS which is unobservable, we introduce a series of unobservable faulty transitions after the \(invoke\) transition to model the faults caused by external WS as is illustrated in figure 1(b).

The CPN model of \(Invoke\) only contains the fault transitions \(t_{f_i}\), which are triggered by the consummation of the token in the output activation place. Once \(t_{f_i}\) is executed, there should be a fault in its output data place and it can be passed to the other activities along the BPEL process execution trace. Again, we define \(Type(t_{f_i}) = t_{inv}\).

### 3.3 Translate structured BPEL activities into CPNs

In this section, we show how to obtain BPEL process CPN by a modular combination of a set of CPNs. We formally define four main structural operators (\(Sequence\), \(Switch\), \(While\), and \(Flow\)) while the other similar operators can be easily translated in the same way.

**Sequence operator** \(sequence(S_1, S_2)\)

\(Sequence\) connects different activities, and the execution order of these activities is the same as their appearance order in the constructor. So we can generate the resulting sequence CPN by simply merging the local intermediate output and input activation places of contractive CPNs (in figure 2(a)).

**Conditional operator** \(Switch\)\(\{(con_i(X_i, V_i), S_i)\}_{i \in I}\)

\(Switch\) represents an alternative execution of the activities \(S_i\) under the conditions \(con_i\). \(X_i\) and \(V_i\) are respectively the variables and constants. For each subprocess \(S_i\), we add a transition \(con_i\) to generate its activation place. Each \(con_i\) takes the common activation input place of \(Switch\), \(X_i\), and \(V_i\) as inputs to \(elaborate\) an input activation place \(a_i^{in}\) for subprocess \(S_i\). So the faults in the relevant data places \(X_i\), \(V_i\) cause the faulty choosing of subprocess. That is, one \(a_i^{in}\) is activated by mistake. This modeling method allow the diagnosis of the control fault in a BPEL process. At the end of the \(Switch\) process, a new
$a^{out}$ is added to replace all the $a^{out}$ of subprocess $S_1$ (in figure 2(c)). Similar operators: Link with its "transitionCondition" ([11]).

**Iterative operator** while$(con(X,V), S_1)$

While iterates the activity $S_1$ execution until the breaking off of the conditions $con(X)$. The CPN graph of While is similar to Switch in which the activation input place of the subprocess $S_1$ is elaborated by the activation input place of While, $X$, and $V$. But in While, the $a^{out}$ of iterative subprocess is also $a^{in}$ of $t_{con}$. Note that $t_{con}$ represents the transition if condition $con$ is true and $t_{con}$ represents the transition if condition $con$ is false (in figure 2(b)). Similar operators: RepeatUntil, ForEach.

**Parallel operator** flow$(\{S_i\}_{i \in I})$

Flow executes the activities $S_i$ in parallel. It terminates when all the activi-
ties are finished (fork-join). So we add $a^{in}$, $a^{out}$, $t^{in}$, and $t^{out}$ to compose the subprocesses together in parallel (in figure 2(d)). Similar operators: *Scope* together with the compensation handlers, event handlers, and fault handlers; *Pick* together with *OnMessage*.

### 3.4 Some remarks on the BPEL model

#### Observable vs unobservable transitions

To distinguish the BPEL activities transitions which are observable and the fault transitions which are not, we divide $T$ into observable transitions $T_{\text{obs}}$ and fault transitions $T_{\text{F}}$ ($T = T_{\text{obs}} \cup T_{\text{F}}$ and $T_{\text{obs}} \cap T_{\text{F}} = \emptyset$). Note that a type function over faults has been defined in definition 1, which associates a fault to its observable transition Type: $T_{\text{F}} \rightarrow T_{\text{obs}}$.

#### Initial and symptom markings of BPEL model net

The initial marking is obtained by marking $P = AP \cup DP$: constant places ($CP \subseteq DP$) are marked as unknown as they cannot be changed by any transition; other data places ($DP \setminus CP$) are marked as black; an activation place $ap \in AP$ which activates the first transition of CPN is marked as black ($b$) and the other $AP$ are marked as 0. The final marking is retrieved from the thrown exception. When fault(s) occurs, an exception will be thrown to specify on which activity, there is a faulty part(s), which corresponds to the places in $DP$. Specially, unmatched or uninitiated data (variable) refers the BPEL process may chose fault execution branch. In this case, the input activation place of the activity will be marked as faulty ($r$). All the other places are marked as unknown ($\ast$) because there is no information of their marking.

#### One-boundness of the BPEL model nets

The resulted CPNs are one-bounded (or safe, means one place can at most contain one token). Concerning the data places, the transitions always consume one token in each input places and produce a new one token in each output places. Concerning the activation places, the one-boundness is guaranteed by the fact that a BPEL process does not allow a subprocess call that can lead to more than one token production in the activation places.

### 3.5 Example (cont’d): CPN model and incidence matrixes

The CPN of the BPEL service *FlightAgent* is constructed as in figure 3. Note that place $d_0$ represents the request message, $d_1$ is a null flight schedule message, $d_3$ and $d_2$ are respectively the corresponding variables defined in BPEL process. $d_4$ stock the intermediate single flight information which is generated by invoke activity $t_s$. Invoke activity $t_o$ continually fills $t_2$ during the execution of process *FlightAgent*. Place $d_5$ is the output flight schedule message of $d_2$. To keep the visibility of the graph, the color functions which do not concern the data dependency are omitted (e.g., color function $C_{a^{in}}$ on the arc $(a^{in}, t_c)$).

We can see that *FlightAgent* CPN contains 12 places and 11 transitions, in which 5 of them are unobservable, and 6 are observable. Table 2 is the forward matrix, table 1 is the backward matrix, and table 3 is the incidence matrix of
FlightAgent got by \( C = C^{+} - C^{-} \). As to space limitation, in the incidence matrices, we use the name of places to represent the colors of the places, for example, \( a^{in} \) represents \( C_{a^{in}} \). Transitions \( t_{fa} \), \( t_{fo} \), \( t_{f1} \), \( t_{f2} \), and \( t_{f3} \) are unobservable activities (in gray boxes). Especially \( t_{fa} \), \( t_{fo} \), and \( t_{f1} \) generate the input fault data of FlightAgent, \( t_{f3} \) represents the external fault in the WS which is invoked by \( t_{S} \), and \( t_{f2} \) represents the external fault in the WS which is invoked by \( t_{O} \).

\[
\text{Type}(t_{fa}) = \text{Type}(t_{f0}) = \text{Type}(t_{f1}) = t_{c} \\
\text{Type}(t_{f2}) = t_{o} \\
\text{Type}(t_{f3}) = t_{s}
\]

Fig. 3. BPEL(a) and CPN model of FlightAgent

4 Diagnosis of BPEL service using CPN

A BPEL process can be considered as a **discrete event system** (DES) of which the classical diagnosis approach is the model based diagnosis ([8]). Given a DES, the diagnosis is to compare the observed behavior of the real system and the
### Table 1. $C^-$: backward matrix of **FlightAgent**

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### Table 2. $C^+$: forward matrix of **FlightAgent**

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### Table 3. $C = C^+ - C^-$: incidence matrix of **FlightAgent**

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simulated behavior of its abstract model to isolate, detect, and explain the faults. After defining a CPN model of BPEL process in the former part, we will formally define the CPN diagnose for the data fault in this section.

4.1 Diagnosis problem

During the execution of a BPEL service instance, we can record the sequence of activities executed within this instance, that we call the trace. This trace belongs to \((T_{obs})^*\). When a fault occurs at some moment of the instance execution, an exception is thrown, what we call in diagnosis literature, a symptom. Exceptions are thrown due to some inconsistency of a part of the services state. The inconsistency can concern either data variables values or activation data (e.g. receiving a bad message, or not receiving an expected message). In both cases, a thrown exception can be represented as a marking where the faulty data (or activation) places are marked with a red token and the others can be marked either as black or unknown.

**Definition 9**  Let \(M\) be a marking, \(M\) is a symptom (exception) marking iff \(\exists p, M(p)(r) \neq 0\). We denote the symptom markings by \(\hat{M}\).

So a diagnosis problem is a 3-tuple of the model, observed behavior, and symptom:

**Definition 10**  A diagnosis problem is a tuple \(D = \langle N, \delta_o, \hat{M} \rangle\):

- \(N\) is a CPN system that represents the model of a BPEL service;
- \(\delta_o\) is an observable trace \(\delta_o \in (T_{obs})^*\);
- \(\hat{M}\) is a symptom marking.

As fault transitions are unobservable, an observation trace always corresponds to multiple characteristic vectors. That is, different intermediate markings can lead to the same symptom marking. We say the symptom marking "covers" all its former markings. We introduce a covering relation as follows:

**Definition 11**  A covering relation \(\preceq\) between colors of \(\Sigma = \{r, b, *\}\) is a partial ordered relation where any color covers itself and the * color covers all colors (i.e. \(\preceq = \{(r, r), (b, b), (*, *), (r, *), (b, *)\}\)). We extend the color covering relation to multisets and markings as follows:

- let \(m, m' \in M^+(\Sigma)\), we have \(m \preceq m'\) iff \(\sum_{c \in \Sigma} m(c) = \sum_{c \in \Sigma} m'(c) \land \forall c \neq *\), \(m'(c) > 0 \Rightarrow m(c) \geq m'(c)\)
- let \(M, M'\) be two markings, we have \(M \preceq M'\) iff \(\forall p \in P, M(p) \preceq M'(p)\)

We give now a definition of a diagnosis:

**Definition 12**  Let \(D = \langle N, \delta_o, \hat{M} \rangle\) be a diagnosis problem, a diagnosis \(\text{Sol} \subseteq T_F\) and \(\text{Sol} \neq \emptyset\) such that: \(M_0 + \mathcal{C} \times \hat{\delta} \preceq \hat{M}\) with \(\hat{\delta}\) is a characteristic vector defined as follows:
∀t ∈ T_{obs}, δ(t) = δ_o(t), where δ_o(t) is the occurrence number of t in δ_o;
∀t_f ∈ Sol, δ(t_f) = 1;
∀t_f ∈ (T_F \ Sol), δ(t_f) = 0.

Note that we restrict the value of a fault transition to 1. This is due to the fact that a fault transition only changes the color of token to red and has no effect on the activation places marking. Even if a fault happens more than once we consider only the occurrence of the fault transition that can explain the symptom (the red token). Thus we restrict the value of the characteristic vector of a fault transition to one or zero (happened and explains the symptom or did not happen).

Definition 13 Let D = \langle N, δ_o, \hat{M} \rangle be a diagnosis problem and Sol be a diagnosis, Sol is minimal iff ∀Sol' ⊂ Sol, Sol' is not a diagnosis.

Definition 14 Let D = \langle N, δ_o, \hat{M} \rangle be a diagnosis problem, the diagnosis solution DS ⊆ 2^F is the set of all possible minimal diagnoses.

4.2 Diagnosis of CPN by inequations system solving

The aim of diagnosis is to explain the symptoms with minimum set of fault. That is, to find the set of traces in the CPN model all of which cover the same observed trace, the faults that appear in those traces represents the diagnosis.

In our model, the symptom is a reachable marking of the CPN model. While we assume that in the initial marking, data is considered as correct (black token marking). So the inequation 1 for the observation δ_o does not hold.

By extending the characteristic vector with the fault occurrences, which consist the diagnosis. The covering relation in inequation 2 holds:

M_0 + C \times \delta \preceq \hat{M}

Let D = \langle N, δ_o, \hat{M} \rangle be a diagnosis problem and let n_i be variables ranging over \{0, 1\}, we construct the characteristic vector δ as follows:

- ∀t ∈ T_{obs}, \bar{\delta}(t) = \bar{\delta}_o(t);
- ∀t_f ∈ T_F \land \delta_o(Type(t_f)) \neq 0, \bar{\delta}(t_f) = n_i;
- ∀t_f ∈ T_F \land \delta_o(Type(t_f)) = 0, \bar{\delta}(t_f) = 0;

We can then construct an inequations system (one inequation for each place) for the diagnosis problem as follows:

\begin{align*}
Q_{\hat{M}} = \begin{cases}
Eq_{p_1} : \hat{M}(p_1) \succeq M_0(p_1) + C(p_1) \bar{\delta} \\
\vdots \\
Eq_{p_i} : \hat{M}(p_i) \succeq M_0(p_i) + C(p_i) \bar{\delta}
\end{cases}
\end{align*}
To each place $p$, we associate an inequation $Eq_p$ where the left part is $l(Eq_p) = \bar{M}(p)$ and the right part is $r(Eq_p) = M_0(p) + C(p, \vec{\delta})$. We divide the set of inequations $Q_{\bar{M}}$ into three subsets:

- $Q_{r\hat{M}} = \{Eq_p | l(Eq_p) = r\}$
- $Q_{b\hat{M}} = \{Eq_p | l(Eq_p) = b\}$
- $Q_{\ast\hat{M}} = \{Eq_p | l(Eq_p) = \ast \lor l(Eq_p) = 0\}$

The diagnosis algorithm executes backward reasoning recursively (algorithm 2) for each inequation $Eq_p \in Q_{r\hat{M}}$ within $Q_{\hat{M}}$ and then combines all the diagnosis results (algorithm 3). In the following, we give first the solution of one inequation and then that of an inequations system.

**One inequation $Q_{r\hat{M}}$ solving**

The part on the right side of an inequation is a multi set composed by color functions, constants, and the corresponding place variables which may have positive or negative coefficients. Solving the inequation consists in canceling the negative terms in the right part, keeping the positive color functions, and evaluating the positive coefficient $n_i$ of red tokens (r) to 1 to explain the red token on the left side of the inequation (algorithm 1). Algorithm 1 looks for the possible minimal diagnosis $N_{r_p}$ corresponding to one symptom place $p$ in a symptom marking. And at the same time, it looks for the candidate inequations $C_{r_p}$ which can explain the symptom place but should be solved further. So to completely solve $C_{r_p}$, we recursively back reason by reconstructing $Q_{r\hat{M}}$, $Q_{\ast\hat{M}}$ until getting all possible causes of the symptom place $p$ (algorithm 2).

**Algorithm 1** Partially solving a $Q_{r\hat{M}}$ inequation: \texttt{solveAnEqu}(Eq$_p$)

**Input:** Eq$_p$: a $Q_{r\hat{M}}$ inequation concerns a place $p$;

**Output:** $< C_{r_p}, N_{r_p} >$: \{ $C_{r_p}$: a set of color functions which generate red tokens; $N_{r_p}$: a set of faulty transitions; \}

1: $C_{r_p} = \emptyset$; $N_{r_p} = \emptyset$;
2: ForEach $n_i \times c_i \in r(Eq_p) = \sum_{i \in I} n_i \times c_i$ do
3: \hspace{1em} if $n_i$ is not a constant and $c_i = r$ then
4: \hspace{2em} $N_{r_p} = N_{r_p} \cup \{t_f\}$; \{records the faulty transition $t_f$ in $N_{r_p}$\}
5: \hspace{1em} else if $c_i$ is a color function concerning place $p'$ then
6: \hspace{2em} $C_{r_p} = C_{r_p} \cup \{c_{p'}\}$; \{records the place $c_{p'}$ if its color $c_i$ is unknown for further solving\}
7: \hspace{1em} else if $c_i$ is a color propagation function $d_{c_i}$ then
8: \hspace{2em} $C_{r_p} = C_{r_p} \cup \{c_{p_i} \in Var(c_i)\}$; \{records all the input places of $c_i$ for further solving\}
9: \hspace{1em} end if
10: end for
11: return $< C_{r_p}, N_{r_p} >$;

**An inequations system $Q_{\bar{M}}$ solving**

By solving each inequation in $Q_{\bar{M}}$ with algorithm 2, we get the diagnosis for
Algorithm 2: Completely solving a $Q^r_M$ inequation: $CSD(Q^r_M, Eq_p)$

**Input:** $Q^r_M = Q^r_M \cup Q^b_M \cup Q^*_{Q^r_M}$: the inequations system; $Eq_p \in Q^r_M$: an inequation to solve;

**Output:** $Sol_p$: a diagnosis solution concerning a symptom place $p$;

1: $Sol_p = \emptyset$;
2: $(C^r_p, N^r_p) = solvAnEqu(Eq_p)$; {get the first back reasoning result, $C^r_p$ need to be resolve further}
3: $Sol_p = Sol_p \cup N^r_p$; {record the current diagnosis}
4: if $C^r_p \neq \emptyset$ then
5:  ForEach $c^p_{p'} \in C^r_p$ do
6:  if $\exists Eq_{p'} \in Q^r_{Q^r_M}$ then
7:   if $l(Eq_{p'}) = *$ then
8:    $Sol_{p'} = Sol_{p'} \cup CSD(Q^r_{Q^r_M} \cup \{r \geq r(Eq_{p'})\} \cup (Q^r_{Q^r_M} \cup Q^*_{Q^r_M}) \setminus \{Eq_p, Eq_{p'}\}, r \geq r(Eq_{p'}))$; {evaluates the $l(Eq_{p'})$ as $r$, reconstructs the inequations system and recursively back reasoning until solved all the related places}
9:   else if $l(Eq_{p'}) = 0$ then
10:    $Sol_{p'} = Sol_{p'} \cup CSD(Q^r_{Q^r_M} \cup \{r' \geq r(Eq_{p'}) + c^p_{p'}\} \cup (Q^r_{Q^r_M} \cup Q^*_{Q^r_M}) \setminus \{Eq_p, Eq_{p'}\}, r \geq r(Eq_{p'}) + c^p_{p'});$ {evaluates the $l(Eq_{p'})$ as $r$ and add a red token on the right side of the inequation to balance $Eq_{p'}$, reconstructs the inequations system, and recursively back reasoning until solved all the related places}
11:   end if
12:  end if
13: end for
14: end if
15: return $Sol_p$;
a inequations system $Q_M$ (algorithm 3). The union set of all the $Sol_p$ is the
diagnosis solution for $Q_M$ which can contain multiple symptoms (faults).

Algorithm 3 Diagnosis solution for an inequations system $Q_M$

**Input:** $Q_M=Q_{rM}^\cup Q_{bM}^\cup Q_{*M}$: the inequations system;
$Sol_p=\emptyset$: a diagnosis solution concerning a symptom place $p$;

**Output:** $D$: a diagnosis solution of $Q_M$;

1: $D=\emptyset$;
2: **ForEach** $Eq_p \in Q_{rM}^\cup$ do
3: $Sol_p=CSD(Q_M, Eq_p)$; {resolve each inequation in $Q_{rM}$ by back reasoning}
4: $D=D \times Sol_p$;
5: **end for**
6: return $D$;

### 4.3 Example (cont’): diagnosis problem and solution of FlightAgent

In our diagnosis scenario, each BPEL process is associated with a monitoring
platform, which records the status of the activities and variables of each execu-
tion instance, and a diagnosis is implemented as a WS, which contains the
initiated (described in subsection 3.4) CPN model of the BPEL. The diagnosis
WS it triggered by the BPEL executer (BPEL execution engine) or invoker (WS,
application, etc) once a symptom is thrown by the executer or invoker, the (ac-
tivation or data) places which correspond to the symptom is marked as $r$ while
the other data places are marked as $*$, and activation places are marked as $0$.
Now suppose we get a series of observed activities $\sigma_0$: $C, W, S, O, W, S, O, W$, and $P$, which means the while iteration is processed twice. Then we construct a
characteristic vector $^\rightarrow \delta_T$: $(t_1 f_a t_2 f_b t_C t_W t_W t_S t_f_2 t_o t_F t_p)=$ $(n_0 n_1 n_2 1 2 1 2 n_4 2 n_3 1)$. Given an initial marking $M_0 = (a^{in} a_2 a_3 a_4 a_5 a^{out} d_0 d_1 d_2 d_3 d_4 d_5) =$ $(b 0 b b b b b)$, we suppose that, in two diagnosis scenarios, we
got two symptom markings $M_{n_1} = (a^{in} a_2 a_3 a_4 a_5 a^{out} d_0 d_1 d_2 d_3 d_4 d_5) =$ $(0 0 0 0 0 * * * * * * * r)$, and $M_{n_2} = (a^{in} a_2 a_3 a_4 a_5 a^{out} d_0 d_1 d_2 d_3 d_4 d_5) =$ $(0 0 0 0 0 r * * * * * * * r)$. For symptom marking $M_{n_1}$, we construct an inequations
system as in equation 3.

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4 $\cup$ is an operator that applies the union operator on couples resulting from the
Cartesian product.
Note that for final marking $M_{n_2}$, we can construct a similar inequations system except $E_{q_{a^*}}$ is different ($r \geq FW^c(C_{a_5}) + 0$) from the one in equation system (3). By applying the diagnosis algorithms, the diagnosis that concerns the symptom marking $M_{n_1}$ is illustrated in figure 4(a) while the diagnosis that concerns $M_{n_2}$ is the $\times$ product of the diagnosis illustrated in figures 4(a+b) as the inequations system for symptom marking $M_{n_2}$ contains one more red token in the activation output place $a^{out}$. In figure 4, we illustrate the diagnosis solving process in structured trees. The nodes represent the inequations needed to be solved and each leaf represents a diagnosis and the union of all leaves is a diagnosis solution.

As a result, for symptom marking $M_{n_1}$, we have the diagnosis: $D_1 = \{\{t_{f_0}\}, \{t_{f_1}\}, \{t_{f_2}\}, \{t_{f_3}\}\}$ represents 4 single faults. Either the input data fault $d_0$, or the input data fault $d_1$, or the transition fault on invoke activity $S$, or the transition

$$\left\{ \begin{aligned}
E_{q_{a_1^n}} & : 0 \geq (r - C_{a_1^n}) \times n_0 - C_{a_1^n} + b \\
E_{q_{a_2}} & : 0 \geq FW^c(C_{a_1^n}) - C_{a_2} \times 2 - C_{a_2} + FW^c(C_{a_4}) \times 2 + 0 \\
E_{q_{a_3}} & : 0 \geq EL^c(C_{a_2}, C_{d_2}) \times 2 - C_{a_3} \times 2 + 0 \\
E_{q_{a_4}} & : 0 \geq FW^c(C_{a_4}) \times 2 - C_{a_4} \times 2 + 0 \\
E_{q_{a_5}} & : 0 \geq EL^c(C_{a_2}, C_{d_2}) - C_{a_5} + 0 \\
E_{q_{a^{out}}} & : * \geq FW^c(C_{a_5}) + 0 \\
E_{q_{a_0}} & : * \geq (r - C_{d_0}) \times n_1 + b \\
E_{q_{a_1}} & : * \geq (r - C_{d_1}) \times n_2 + b \\
E_{q_{a_2}} & : * \geq FW^c(C_{d_0}) - C_{d_2} + (r - C_{d_2}) \times n_3 + b \\
E_{q_{a_3}} & : * \geq FW^c(C_{d_4}) + (EL^c(C_{d_5}) - C_{d_5}) \times 2 + (r - C_{d_2}) \times n_4 + b \\
E_{q_{a_4}} & : * \geq (EL^c(C_{d_2}) - C_{d_3}) \times 2 + (r - C_{d_3}) \times n_3 + b \\
E_{q_{a_5}} & : * \geq EL^c(C_{d_5}) - C_{d_5} + b \\
\end{aligned} \right. $$

(3)
fault on invoke activity $O$. Concerning the symptom marking $M_{n2}$, the diagnosis is extended as: $D = D_1 \cup D_2$, where $D_2$ concerns the red token in activation place $a^{out}$. As illustrated in figure 4(b), $D_2 = \{t_{f_a}\}, \{t_{f_b}\}, \{t_{f_0}\}$. So, we get diagnosis $D = \{t_{f_0}\}, \{t_{f_a}\}, \{t_{f_a}, t_{f_b}\}, \{t_{f_0}, t_{f_0}\}$, i.e., the fault is on input data place $d_0$, or on transition $O$, or on input activation place $f_a$ and invoke activity $C$, or on input activation place $f_a$ and invoke activity $S$.

5 Related work

Automata, process algebra, and Petri nets are the most popular DES models. We refer the reader to [14] for the surveys of formal methods of Web services modeling. The major method for diagnosing a DES is trajectory unfolding. Unfolding method is used on the observable trajectory of system evolution to find the faulty states as the diagnosis. For example, [16] proposes a decentralized model-based diagnosis algorithm based on the PNs model ([10]) by inversely unfolding the trajectory. But in [16], local diagnoser does not support iteration in BPEL processes.

We can also adapt the FlightAgent example according to the modeling methods of [2] by modeling the states of the BPEL service as places and activities as transitions. As this modeling approach loses the data dependency which cannot ensure the diagnosis is as minimal as ours. [12] models a modular interacting system as a set of place-bordered Petri nets and proposes a distributed online diagnosis which applies algebra calculations from the local models and the communicating messages between them. But when applying [12] on the FlightAgent example gets the explosion of the state space because the partition of the variables and messages into subtle parts, and its simple Petri nets definition are too limited to deal with the data aspects.

There are some works that model the WS system with other types of models. In [5], a system is modeled with process algebra containing faulty behavior models. The diagnosis is done by comparing all possible action traces with the observations. All the faulty actions of the matched traces are the diagnosed faults. But [5] models and diagnosis the general WS applications but not a concrete WS specification language. [15] models BPEL services as enriched synchronized automata pieces and diagnose by trajectory reconstruction from observation while the algorithm is incapable for diagnosing the control fault in the process.

A similar diagnosis approach has been proposed in [1], of which we use the same data dependency relation. But [1] does not support loops in WS process while we represent loops as the occurrence in a characteristic vector. In such way, we solve the loops without extra cost. The consistency-base diagnosis approach proposed in [1] is more abstract but loses the precision on modeling level. But we believe that the two methods can get the same minimal diagnosis.

We use the places to represent the data instead of states of the DES in other works. When simulating the CPN model, the states of the data is more intuitive. And the markings of CPN represent the different states which contain plenteous information and can be formally analyzed.
6 Conclusion

Our CPN modeling approach addresses diagnosis of data fault(s) of orchestrated Web services. The paper constructs a model for the faulty data and faulty activities in a BPEL process. We construct an inequations system for the diagnosis of a BPEL service. And a concrete inequations solving algorithm is proposed. The diagnosis takes advantage of the matrix calculation, which helps to improve the effectiveness of the diagnosis. The interpretation of happened (1) or not happened (0) status of the fault transitions avoids the unfolding of Petri nets or trajectory reconstruction. So the iterative structure in BPEL services does not increase the calculation complexity of the diagnosis.

Our diagnosis approach can be easily extended into the distributed environments according to the approach proposed in [12] by defining a proper composition protocol of the CPNs. And we believe that the diagnosability analysis can also be done using algebra analysis based on the incidence matrix, which is another ongoing work.

References