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Simulating Petri Nets with Inhibitor and Reset Arcs

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Abstract. Event logs of software systems are used to analyze their behaviour and inter-component interaction. Artificial event logs with desirable specifics are needed to test algorithms supporting this type of analysis. Recent methods allow to generate artificial event logs by simulating ordinary Petri nets. In this paper we present the algorithm generating event logs for Petri nets with inhibitor and reset arcs. Nets with inhibitor arcs are more expressive than ordinary Petri nets, and allow to conveniently model conditions in real-life software. Resets are common in real-life systems as well. This paper describes the net simulation algorithm, and shows how it can be applied for event log generation.

Keywords: Petri nets; inhibitor arcs; reset arcs; simulation; event logs

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Симуляция сетей Петри с ингибиторными дугами и дугами сброса

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Аннотация. Журналы событий программных систем используются для анализа их поведения и взаимодействия между компонентами. Искусственные журналы событий с подходящими свойствами необходимы для тестирования алгоритмов, используемых для такого анализа. Современные методы позволяют генерировать искусственные журналы событий в результате симуляции обычных сетей Петри. В этой статье мы представляем алгоритм, генерирующий журналы событий для сетей Петри с ингибиторными дугами и дугами сброса. Сети с ингибиторными дугами более выразительны, по сравнению с классическими сетями Петри, и позволяют удобно моделировать условия в реальном программном обеспечении. Операции сброса также распространены в реальных системах. В этой статье описывается алгоритм симуляции сетей Петри с ингибиторными дугами и сбросами, а также показано, каким образом его можно применять для генерации журнала событий.

Ключевые слова: сети Петри; ингибиторные дуги; дуги сброса; симуляция; журналы событий

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1. Introduction

Recently, process analytics evolved into an advanced field of computer-based technology. Automated methods have been created to find bottlenecks and inefficiencies in process models of information systems.

One particular technology that helps to automate process analysis is process mining [1]. Experts in this technology employ algorithms and methods which use the records of a system behaviour, which are called «event logs» or «system logs». This information can be explored to discover a model of how the real process behaves [1].

An existing process model runs can be aligned to the records of an event log to check if the model conforms to the real system behaviour [2]. The field also provides an expert with method to improve/repair processes and process models.

The process simulation methods are also applied in the field of process analytics [3].

Recently, it has been stated that process mining and simulation form “a match made in heaven” [4]. In particular, process model simulation can be applied to look in the future of a process, and to test *what-if* alternative scenarios possible because of process change. Moreover, the development of process mining algorithms is impossible without sample models and event logs with a suitable characteristics [1]. Sample event logs can be generated using the process model simulation methods [5]–[8]. Process mining and simulation can also be matched in other way. The results of process discovery and conformance checking can be applied to improve simulation models.

Various modelling formalisms are employed in the field of process analytics [1], [3]. Among them, the language of Petri nets is one of the most well-established, well-researched, simple, and commonly-used modelling languages [9]. Lots of process discovery and analysis techniques are based on this language [1].

A strength of the Petri net language is that on top of simply defined P/T-nets many extensions have been built. These are high-level Petri nets: Coloured Petri nets [10], Nested Petri nets [11], Object nets [12] etc. Method to simulate Petri nets of various types have been proposed in literature. However, for many types of Petri nets still there are no simulation techniques/tools.

This paper presents an approach and a tool to simulate Petri nets with reset and inhibitor arcs. The addition of these arc types improves the net expressiveness significantly. Thus, these nets are used when the process cannot be (conveniently) modelled by P/T-nets.

This paper is organized as follows. Section 2 defines models and event logs. In Section 3 the main contribution is presented: algorithms to simulate Petri nets with inhibitor and reset arcs. These algorithms are implemented in the tool which is described in Section 4. Finally, Section 5 concludes the paper.

2. Petri Nets and Event Logs

In this section, we define process models and event logs. Let $\mathbb{N}$ denote the set of all non-negative integers, and $\mathbb{N}_+ = \mathbb{N}\backslash\{0\}$.

2.1 Ordinary Petri nets

Petri nets are directed bipartite graphs which allows for modelling and representation of processes in information systems [13]. More formally, an *ordinary Petri net* is a triple $N = (P, T, F)$, where P and T are two disjoint sets of places and transitions, and $F \subseteq (P \times T) \cup (T \times P)$ is a flow relation. As graphs, Petri nets have convenient visual representation. Fig. 1 shows an example model.

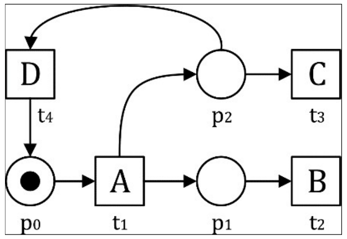


Fig. 1. An ordinary labelled Petri net

Places are shown by circles, transitions are shown by boxes, the flow relation is depicted using ordinary directed arcs. In fig. 1, there are three places (p_0, p_1, p_2) and four transitions (t_1, t_2, t_3, t_4). Transitions are labelled with activity names from the set $\mathcal{A} \cup \{\tau\}$. In the example, $\mathcal{A} = \{A, B, C, D\}$. Labels are placed inside the transition boxes. An Petri net can contain invisible *(silent)* process actions which are labelled with τ. Labels are assigned to transitions via a *labelling function* $\lambda: T \to \mathcal{A} \cup \{\tau\}$.

A state of an ordinary Petri net is called its *marking*. It is a function $M : P \to \mathbb{N}$ assigning natural numbers to places. In figures, a marking M can be designated by putting $M(p)$ black tokens into a place p of the net. By M_0 we denote the initial marking. For example, the initial marking of the net from Fig. 1 consists of a single token in the place p_0.

A transition represents an activity of a process. It is enabled in a current marking if in each of its input places (for $t \in T$ input places are $\bullet t = \{p \mid (p,t) \in F\}$) there enough tokens, that is $\forall p \in \bullet t: M(p) \geq 1$. An enable transition may fire that changes a marking of the net. It consumes tokens from the input places, and produces tokens to output places (for $t \in T$ input places are $t \bullet = \{p \mid (t,p) \in F\}$).

Consider a model from fig. 1: t_1 is the only enabled transition in the initial marking. It may fire, that corresponds to an occurrence of activity "A". Then, the transition consumes a single token from p_0 and produces tokens to p_1 and p_2. Fig. 2 illustrates this firing. The firing is local, each transition fires independently from other transitions.

2.2 Petri nets with Inhibitor and Reset Arcs

In this paper, we consider Petri nets with arcs of two additional types: reset and inhibitor arcs. These nets also contain places, transitions, and ordinary control flow arcs.

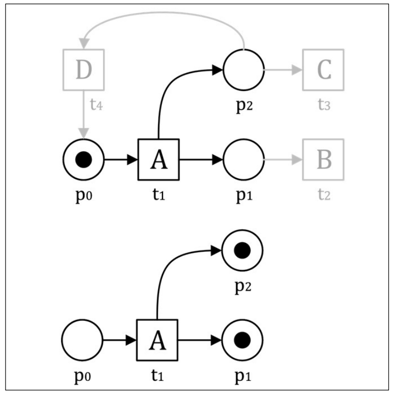


Fig. 2. Firing a Petri net

A labelled Petri net with weights, inhibitor and reset arcs (WIR Petri net) is a tuple $N_{WIR} = (P, T, F, W, R, I, \lambda)$, where

- (P, T, F) is an ordinary Petri net,
- $W \in F \to \mathbb{N}_+$ is an arc weight function,
- $R \subseteq P \times T$ is a function defining reset arcs,
- $I \subseteq P \times T$ is an inhibiting relation,
- and $\lambda: T \to A \cup \{\tau\}$ is a labelling function.

Fig. 3 shows an example WIR Petri net.

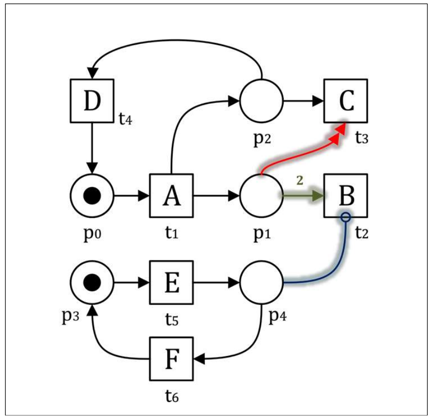


Fig. 3. A WIR Petri net

A *reset arc* removes all tokens from the place no matter of their number. These arcs also called *clear* arcs [14].

In Fig. 3, there is a reset arc from the place p_1 to the transition t_3 labelled with "C". Reset arcs are denoted with double arrows at the end. Note that the net contains a loop of two actions "A" (t_1) and "D" (t_4). The possible sequence of firings is $< t_1, t_4, t_1, t_4, t_1, t_4, t_3 >$. Before the last step, p_1 will contain 3 tokens all of which will be removed by the firing of t_3.

An *inhibitor arc* [15], [16] can be from a place to a transition. This transition cannot fire if there is a token in place connected with the transition using an inhibitor arc. $\circ t = \{p \mid (p,t) \in I\}$ denotes the set of inhibiting places for t. That is, an inhibiting place allows to prevent the transition firing. Transitions consume no tokens through inhibitor arcs.

Inhibitor arcs are shown with small circles instead of arrows at the end. In Fig. 3, there is a reset arc from the place p_4 to the transition t_2 labelled with "B". Thus, t_2 can not fire if there is a token in p_4 no matter how many tokens are in p_1. The whole part of the model that consists of places p_3 and p_4, transitions t_5 and t_6 is a switch with two possible states: open (there is a token in p_3) / closed (there is a token in p_4).

The firing of t_5 closes the switch and deprecates the firing of t_2. Thus, only t_3 is able to clear tokens from the place p_1 if there is a token in p_2. The firing of t_3 will end the process, because it will consume and remove all tokens from the upper part of the net.

The firing of t_6 opens the switch. Then, t_2 may consume tokens from p_1 independently of tokens in other places. Note that the arc from p_1 to t_2 has a weight of 2. Thus, each firing of t_2 consume exactly 2 tokens, and t_2 can not fire if there is only one token in p_1. Note that a particular WIR Petri net can contain zero number of reset and inhibitor arcs.

Marking of a WIR Petri net is defined in the same way as for an ordinary Petri net. But the firing rule is slightly different for WIR Petri nets. Each marking change is called *step*. In this paper, we assume that each step consists of a single transition firing. The step from Fig. 2 is denoted by $M_0[t_1\rangle M'$, where $M'(p_1) = M'(p_2) = M'(p_3) = 1$ and $M'(p_0) = M'(p_4) = 0$.

2.3 Event Logs

In this paper, we apply process model simulation to generate event logs with records of the behavior. We define an *event log* as a finite multiset of traces $\in \mathcal{B}(\mathcal{A})$ [1]. A trace $\sigma \in \mathcal{A}^*$ is a finite sequence of events from the set $\mathcal{A}$. Note that transitions of a WIR Petri net are labelled with elements of $\mathcal{A}$. The only transitions which firing leaves no events are silent τ-transitions.

Technically, we record the event logs in XES (Extensible Event Stream) format[2] that will be considered in more detail in Section 4.

3. Petri Net Simulation Algorithm

This section describes the algorithm to simulate labelled WIR Petri nets.

The main idea of the algorithm is to iterate over all transitions and fire one of them at each iteration, recording corresponding events to the log. This procedure is performed in the main generating function called *generateTrace* (see Algorithm 1).

```
Input: transitions, initialMarking, finalMarking,
settings as {maxNumberOfSteps, maxIterations, isRemovingUnfinished Traces}
Output: generated trace or NULL
function generateTrace
trace ← NULL;
replayCompleted ← false;
addTraceToLog ← false;
iteration ← 0;
repeat
   moveToInitialState();
   trace ← createTrace();
   stepNumber ← 0;

      while stepNumber < maxNumberOfSteps
          and not replayCompleted do

         transition ← chooseNextTransition();
         if transition = NULL then
            trace ← NULL;
            break;
         end if

         fire(transition, trace);
         replayCompleted ← isCompleted(finalMarking);
         stepNumber ← stepNumber + 1;
      end while

      iteration ← iteration + 1;
   until (iteration >= maxIterations or
      not isRemovingUnfinishedTraces or replayCompleted)

   if not replayCompleted
         and isRemovingUnfinishedTraces then
      trace ← NULL;
   end if
      return trace;
   end function
```

Algorithm 1. One trace generation

[1] Here $\mathcal{B}(\mathcal{A}^*)$ denotes all multisets over $\mathcal{A}^*$, where $\mathcal{A}^*$ — all finite sequences with elements from $\mathcal{A}$.

[2] http://www.xes-standard.org/

This algorithm works as follows. We have *maxIterations* attempts to reach the final marking of the net. By default this number is 10. The function *moveToInitialState* initiates the trace generation by setting a marking of the to M_0. Then, we create an empty trace by calling *createTrace*.

At each step of the main loop, the algorithm chooses an enabled transition in the *chooseNextTransition*, and fire it (function *fire*). The function *fire* changes a marking of the net and writes an event to the trace. Then we call the function *isCompleted* to check if we reached the final marking and update *replayCompleted*. This loop iterates until we reach the final marking (*replayCompleted = true*) or exceed the specified limit of steps for one trace *maxNumberOfSteps*.

When we cannot find an enabled transition which is ready to fire, we clear the unfinished trace and begin a new attempt.

If no one of 10 attempts succeeded, we return NULL which will be recorded as an empty trace to the event log. Note that there is a setting of the prototype tool that removes all empty and unfinished traces.

The *chooseNextTransition* function selects an enabled transition using a specified rule. The most basic implementation of this function is shown in Algorithm 2. Here, the random transition among all enabled and noise transitions is selected.

```
Input: allTransitions, noiseTransitions
Output: selected transition or NULL
function chooseNextTransition(allTransitions, noiseTransitions)
   enabledTransitions ← findEnabledTransitions();
   return random transition among enabledTransitions
      and noiseTransitions or NULL;
end function
```

Algorithm 2. Looking for the next transition

This algorithm is based on the algorithm for ordinary Petri nets [17], and thus, is able to add noise to the event log. More complex rules to select the enabled transition can be applied. For example, priorities of preferences can be assigned to the transitions which affect the order of their firing. If there is no enabled transition, then NULL is returned.

To check if a transition t is enabled, we ensure that all input places connected with t with the help of ordinary arcs have enough tokens. Besides that, we check that places connected with t with the help of inhibitor arcs don't contain any tokens. Reset arcs don't affect if a transition is enabled or not. Algorithm 3 shows how this is done.

```
Input: allTransitions
Output: list of enabled transitions
function findEnabledTransitions(allTransitions)
   enabledTransitions ← ∅;

   for transition in allTransitions do
      enabled ← true;
      for arc in transition.inputArcs do
         if arc.place.numberOfTokens < arc.weight then
            enabled ← false;
            break;
            end if
         end for
         if not enabled then
```

```
13:             continue;
14:          end if
15:          for arc in transition.inhibitorArcs do
16:             if arc.place.numberOfTokens > 0 then
17:                enabled ← false;
18:                break;
19:             end if
20:          end for
21:          if enabled then
22:             enabledTransitions.add(transition);
23:          end if
24:       end for
25:       return enabledTransitions;
26:    end function
```

Algorithm 3. Finding enabled transitions

Algorithm 4 shows the transition firing function. This function produces and consumes tokens, and then adds an event corresponding to this transition to the trace. The basic implementation is shown which considers only transition names. There are much more complicated implementations of this function for time-driven, resources, and priorities generation modes.

```
Input: transition, place
Output: traced events
1: function fire(transition, trace)
2:    for arc in transition.inputArcs do
3:       arc.place.consumeToken(arc.weight);
4:    end for
5:    for arc in transition.inputResetArcs do
6:       arc.place.consumeAllTokens();
7:       end for
8:
9:    log transition to trace or perform some noise event
10:
11:      for arc in transition.outputArcs do
12:         arc.place.produceTokens(arc.weight);
13:      end for
14:   end function
```

Algorithm 4. Firing function

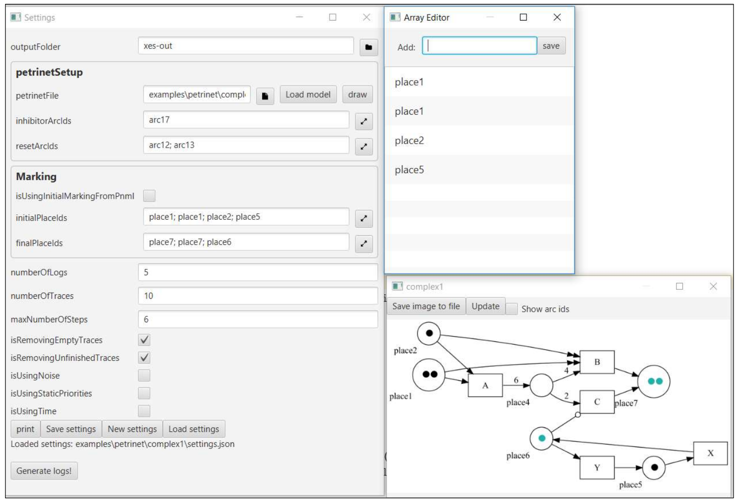
4. Prototype Tool

The presented event log generation algorithm has been implemented as a prototype tool. It is written in Java and Kotlin programming languages. In this section, we consider the tool. The tool consists of two parts: *Generation Setup* unit and *Generation* unit.

4.1 Preparing for generation

In preparation part we receive settings from the GUI (see fig. 4) or read a JSON (see fig. 5) file. Settings from JSON are validated. Then we load the model from a PNML[3] file and prepare this model for generation. Inhibitor and reset arcs could be either specified in settings file, or loaded from the PNML file. The initial and final markings are loaded in the same manner.

[3] www.pnml.org/



outputFolder: xes-out

petrinetSetup

petrinetFile: examples\petrinet\compl

inhibitorArcIds: arc17

resetArcIds: arc12; arc13

Marking

isUsingInitialMarkingFromPnml: ☐

initialPlaceIds: place1; place1; place2; place5

finalPlaceIds: place7; place7; place6

numberOfLogs: 5

numberOfTraces: 10

maxNumberOfSteps: 6

isRemovingEmptyTraces: ✓

isRemovingUnfinishedTraces: ✓

isUsingNoise: ☐

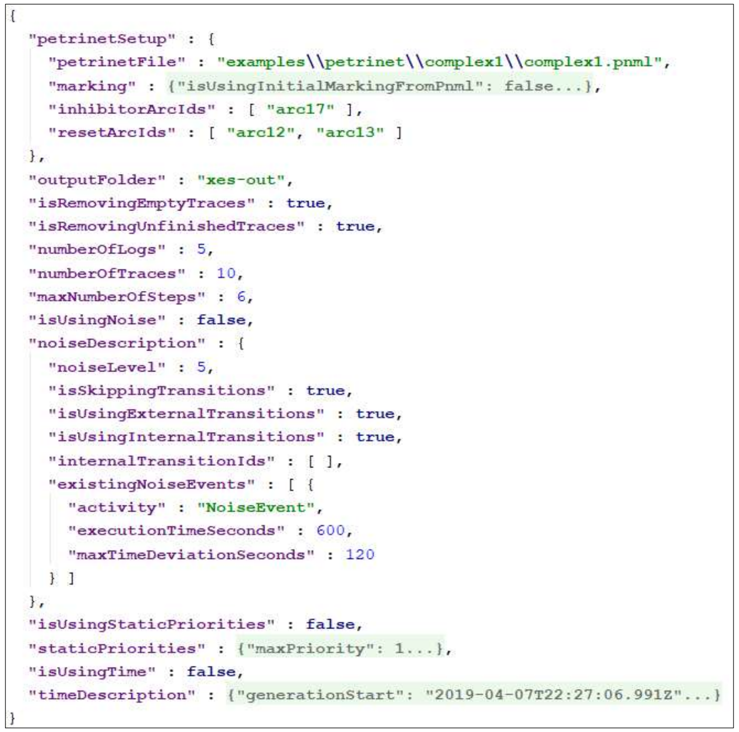
isUsingStaticPriorities: ☐

isUsingTime: ☐

Loaded settings: examples\petrinet\complex1\settings.json

place1
place1
place2
place5

Fig. 4. Tool GUI



```
{
  "petrinetSetup" : {
    "petrinetFile" : "examples\\petrinet\\complex1\\complex1.pnml",
    "marking" : {"isUsingInitialMarkingFromPnml": false...},
    "inhibitorArcIds" : [ "arc17" ],
    "resetArcIds" : [ "arc12", "arc13" ]
  },
  "outputFolder" : "xes-out",
  "isRemovingEmptyTraces" : true,
  "isRemovingUnfinishedTraces" : true,
  "numberOfLogs" : 5,
  "numberOfTraces" : 10,
  "maxNumberOfSteps" : 6,
  "isUsingNoise" : false,
  "noiseDescription" : {
    "noiseLevel" : 5,
    "isSkippingTransitions" : true,
    "isUsingExternalTransitions" : true,
    "isUsingInternalTransitions" : true,
    "internalTransitionIds" : [ ],
    "existingNoiseEvents" : [ {
      "activity" : "NoiseEvent",
      "executionTimeSeconds" : 600,
      "maxTimeDeviationSeconds" : 120
    } ]
  },
  "isUsingStaticPriorities" : false,
  "staticPriorities" : {"maxPriority": 1...},
  "isUsingTime" : false,
  "timeDescription" : {"generationStart": "2019-04-07T22:27:06.991Z"...}
}
```

Fig. 5. Generation settings in JSON

After that we create an instance of special class *GenerationHelper*, which encapsulates the main code for choosing transitions, looking for enabled transitions, handling noise and artificial log events if it is needed. There are different helpers for simple generation, generation with priorities, and generation with time.

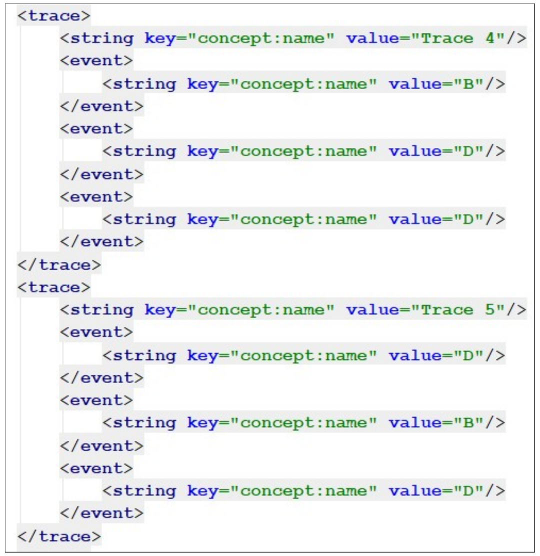
Also, we convert each transition to a special loggable transition-related class which is used during generation. They contain methods of event recording to a trace. Such a class also consumes tokens from input places and produces tokens to output places. Methods to check if a transition is enabled are also here.

4.2 Preparing for generation

A singleton class is used to record the event log. We setup this logging class. It uses the OpenXES[4] library with the help of which we can write XES log files. The XES format is common for the field of process mining [1]. OpenXES library creates a separate file for each log. A fragment of the example output in XES file is shown in fig. 6. This example contains two traces with names “Trace 4” and “Trace 5”. These names should be unique.

The first trace is of the three events: “B”, “D”, and “D”. Note that XES is XML-based and is easy-to-read for a machine or a human.

Then we use a *Generator* class to launch the main generation method (see Algorithm 1), passing a *generationHelper* to this class.



```
<trace>
    <string key="concept:name" value="Trace 4"/>
    <event>
        <string key="concept:name" value="B"/>
    </event>
    <event>
        <string key="concept:name" value="D"/>
    </event>
    <event>
        <string key="concept:name" value="D"/>
    </event>
</trace>
<trace>
    <string key="concept:name" value="Trace 5"/>
    <event>
        <string key="concept:name" value="D"/>
    </event>
    <event>
        <string key="concept:name" value="B"/>
    </event>
    <event>
        <string key="concept:name" value="D"/>
    </event>
</trace>
```

Fig. 6. Fragment of XES file

4.3 Tool Usage

Let us test our tool on the model from the fig. 7.

The initial marking consists of four tokens (shown as black dots): one token lies in *place2*, one is in *place5*, and two tokens are in *place1*. Our goal is to reach the final marking (shown as green dots): two tokens in *place7*, and one token in *place6*.

Transition C is enabled only when place place6 is empty. C consumes 2 tokens from *place4* and produces a token to *place7*. Transition B removes all tokens in places *place1* and *place2*. When this transition fires, it consumes 4 tokens from *place4* and produces a token to *place7*. Thus, B can not

[4] http://www.xes-standard.org/openxes/start

fire before A. At each step either X or Y is enabled, so these transitions may produce a trace of any length. We set-up our tool to remove unfinished traces and limited max number of steps to 10. The result of the generation is shown in fig. 8.

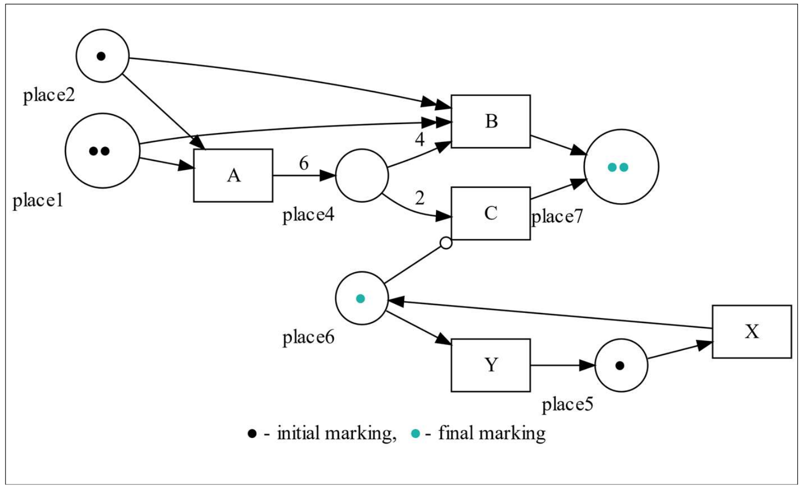
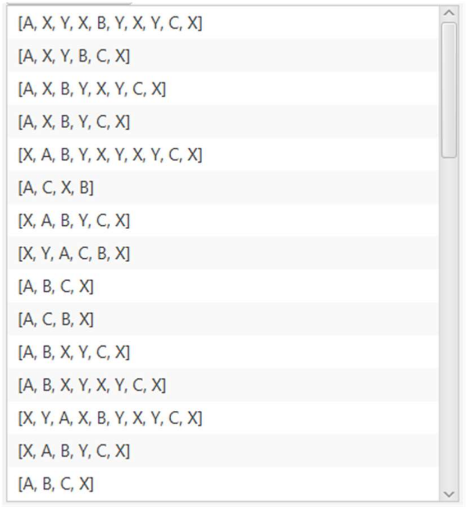


Fig. 7. Petri net used for log generation



```
[A, X, Y, X, B, Y, X, Y, C, X]
[A, X, Y, B, C, X]
[A, X, B, Y, X, Y, C, X]
[A, X, B, Y, C, X]
[X, A, B, Y, X, Y, X, Y, C, X]
[A, C, X, B]
[X, A, B, Y, C, X]
[X, Y, A, C, B, X]
[A, B, C, X]
[A, C, B, X]
[A, B, X, Y, C, X]
[A, B, X, Y, X, Y, C, X]
[X, Y, A, X, B, Y, X, Y, C, X]
[X, A, B, Y, C, X]
[A, B, C, X]
```

Fig. 8. Resulting traces

Let us look at some trace, for example: $<A, X, B, Y, C, X>$. First fired transition was A, and it produced 6 tokens to *place4*. Then X fired. It consumed a token from *place5* and produced one to *place6*. C cannot fire in this marking. Thus, B fires. 4 of 6 tokens was consumed from *place4*, and one token produced to *place7*. Then Y fired and «opened» C. C has been fired just after Y was fired, when a token has been removed from *place6*. B and C were fired once each, and produced 2 tokens in total to *place7*. *place1* and *place2* were cleared by B. The last event was X, which placed a token to *place6*. At the end of this run all tokens reside in the final marking.

5. Conclusion

In this paper, we have presented the algorithm to simulate a process model in the form of weighted labelled Petri net with inhibitor and reset arcs. This algorithm can be applied to generate event logs from the event log. Proposed algorithm continues the previous works on Petri net simulation with the purpose of generating artificial event logs. The prototype implementation is based on Gena tool[5].

We have plans for future work. Firstly, we plan to comprehensively evaluate the proposed algorithm on artificial and real-life process models. For now, we just tested it on sample models to check algorithm validity. Secondly, we also plan to improve the prototype implementation and make it stable and usable. Thirdly, Gena is able to simulate timed process models, models with resources, data, add noise to an event log [8], [17]. Recently, an extension for Gena to simulate the multi-agent system has been proposed [18]. We plan to merge these extensions and the algorithm presented in this paper. Then, it will be possible to simulate WIR Petri nets with time/resources, and data.

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