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Applying Probability Propagation Nets

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Applying Probability Propagation Nets

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Abstract. In this paper, we demonstrate by means of two examples how to work with probability propagation nets (PPNs). The first, which comes from the book by Peng and Reggia [1], is a small example of medical diagnosis. The second one comes from [2]. It is an example of operational risk and is to show how the evidence flow in PPNs gives hints to reduce high losses. In terms of Bayesian networks, both examples contain cycles which are resolved by the conditioning technique [3].

1 Introduction

Our estimation of probability propagation nets (PPNs) has changed in the course of time. Originally, it was intended to make the calculations in Bayesian networks (BNs) more transparent by means of a Petri net approach [4,5,6,7,8]. Later on, PPNs proved to be a good choice as a means to work with for solving probabilistic problems, mainly because of the linear structure of Petri nets and their ability to represent logical proofs [9].

The paper is organized as follows. After an introduction into the conditioning technique [3] for coping with cycles in chapter 2. It will be demonstrated in chapter 3 how to formalize the medical diagnosis approach by Peng and Reggia by means of PPNs. Chapter 4 deals with representing operational risk with PPNs. In the example, which is borrowed from [2], will be shown how to curtail considerable losses, i.e. which one of the input parameters should urgently be changed to reduce the losses.

2 Conditioning

Conditioning is one of several techniques to cope with loops [3]. Due to loops it might happen that in a calculation a certain probability is considered too often as demonstrated in the following example.

Successive transition firings in Fig. 1(a) result in

$$\begin{aligned} \pi(a) &= 0.4 \\ \pi(b \wedge c) &= 0.4 \cdot 0.03 = 0.012 \\ \pi(d) &= 0.4 \cdot 0.03 \cdot 0.5 = 0.006 \end{aligned}$$

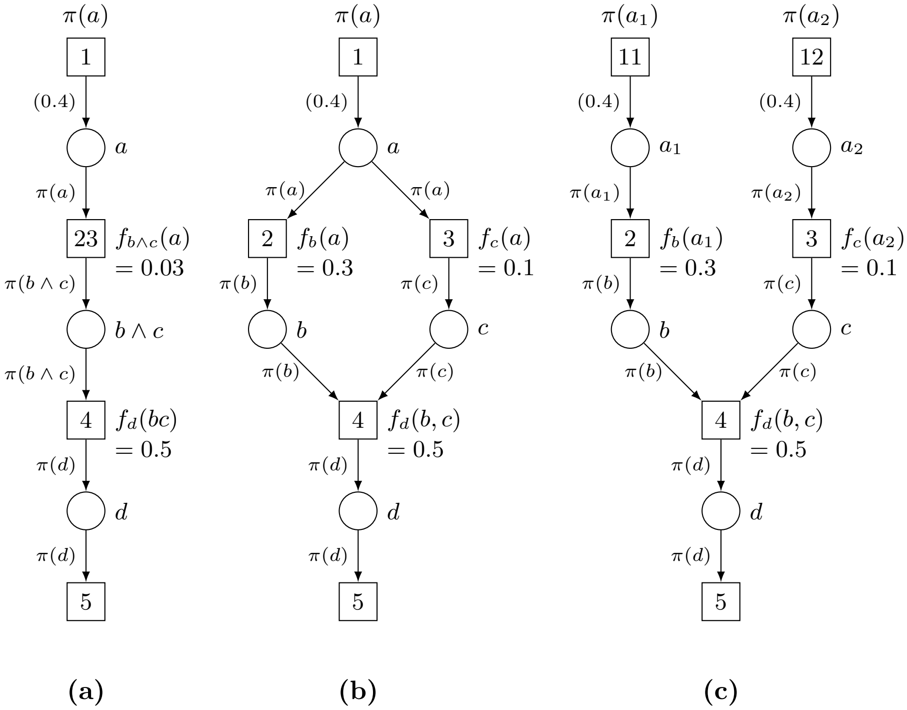


Fig. 1.

In Fig. 1(b) we may take the nodes 2, 3, b, c as some inner structure of the nodes 23 and $b \wedge c$ of Fig. 1(a). Then there should be no difference in the respective values of $\pi(d)$. But now the successive transition firings in Fig. 1(b) result in

$$\begin{aligned} \pi(a) & && = 0.4 \\ \pi(b) & = 0.4 \cdot 0.3 && = 0.12 \\ \pi(c) & = 0.4 \cdot 0.1 && = 0.04 \\ \pi(d) & = 0.4 \cdot 0.3 \cdot 0.4 \cdot 0.1 \cdot 0.5 && = 0.0024 \end{aligned}$$

Because of the two factors 0.4 the value $\pi(d) = 0.0024$ is obviously wrong. (Note that transition $\pi(a)$ had to fire twice.) There is another difficulty with the net in Fig. 1(b): It is no dependency net because of the cycle $(a, 2, b, 4, c, 3, a)$. To surmount this defect, we switch to the dependency net of Fig. 1(c) where transition 1 and place a are cut into two nodes 11, 12 and a_1, a_2, respectively. But also in this net, we are faced with the wrong value $\pi(d) = 0.0024$.

The actual conditioning is a simplification by hypothetically assuming $\pi(a_1) = \pi(a_2) = 1.0$, i.e. by replacing both arc inscriptions 0.4 of the arcs $(11, a_1)$ and $(12, a_2)$ by 1.0. Thus we exploit that 1.0 is idempotent with respect to multiplication (i.e. $1.0 \cdot 1.0 = 1.0$). This yields

$$\begin{aligned}
\pi(a_1) &= \pi(a_2) && = 1.0 \\
\pi(b) &= 1.0 \cdot 0.3 && = 0.3 \\
\pi(c) &= 1.0 \cdot 0.1 && = 0.1 \\
\pi(d) &= 1.0 \cdot 0.3 \cdot 1.0 \cdot 0.1 \cdot 0.5 = 0.3 \cdot 0.1 \cdot 0.5 && = 0.015
\end{aligned}$$

The last step is to multiply these values by the original value $\pi(a_1) = \pi(a_2) = 0.4$ to get the correct values

$$\begin{aligned}
\pi(a_1) &= \pi(a_2) = 0.4 \\
\pi(b) &= 0.12 \\
\pi(c) &= 0.04 \\
\pi(d) &= 0.006\ .
\end{aligned}$$

What remains to be demonstrated is a generalization of the dependency net in Fig. 1(c) for probability vectors.

The counterpart to the wrong calculation is

$$\begin{aligned}
\pi(a_1) &= \pi(a_2) = (0.4, 0.6) \\
\pi(b) &= \pi(a_1) \cdot f_b(a_1) = (0.4, 0.6) \cdot \left[\begin{smallmatrix} 0.3 & 0.7 \\ 0.0 & 1.0 \end{smallmatrix}\right] = (0.12, 0.88) \\
\pi(c) &= \pi(a_2) \cdot f_c(a_2) = (0.4, 0.6) \cdot \left[\begin{smallmatrix} 0.1 & 0.9 \\ 0.0 & 1.0 \end{smallmatrix}\right] = (0.04, 0.96) \\
\pi(d) &= (\pi(b) \times \pi(c)) \cdot f_d(b, c) = ((0.12, 0.88) \times (0.04, 0.96)) \cdot f_d(b, c) \\
&= (0.0048, 0.1152, 0.0352, 0.8448) \cdot \begin{bmatrix} 0.5 & 0.5 \\ 0.0 & 1.0 \\ 0.0 & 1.0 \\ 0.0 & 1.0 \end{bmatrix} = (0.0024, 0.9976)
\end{aligned}$$

Now a double conditioning is required, one for 0.4 and one for 0.6. The corresponding hypothetical values are $(1.0, 0.0)$ and $(0.0, 1.0)$ which we bring together in the matrix $\left(\begin{smallmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{smallmatrix}\right)$.

The results are

$$\begin{aligned}
\pi(a_1) &= \pi(a_2) = \left(\begin{smallmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{smallmatrix}\right) \\
\pi(b) &= \pi(a_1) \cdot f_b(a_1) = \left(\begin{smallmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{smallmatrix}\right) \cdot \left[\begin{smallmatrix} 0.3 & 0.7 \\ 0.0 & 1.0 \end{smallmatrix}\right] = \left(\begin{smallmatrix} 0.3 & 0.7 \\ 0.0 & 1.0 \end{smallmatrix}\right) \\
\pi(c) &= \pi(a_2) \cdot f_c(a_2) = \left(\begin{smallmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{smallmatrix}\right) \cdot \left[\begin{smallmatrix} 0.1 & 0.9 \\ 0.0 & 1.0 \end{smallmatrix}\right] = \left(\begin{smallmatrix} 0.1 & 0.9 \\ 0.0 & 1.0 \end{smallmatrix}\right) \\
\pi(d) &= (\pi(b) \times \pi(c)) \cdot f_d(b, c) = \left(\left(\begin{smallmatrix} 0.3 & 0.7 \\ 0.0 & 1.0 \end{smallmatrix}\right) \times \left(\begin{smallmatrix} 0.1 & 0.9 \\ 0.0 & 1.0 \end{smallmatrix}\right)\right) \cdot f_d(b, c) \\
&= \begin{pmatrix} \scriptstyle (0.3,0.7)\ \times\ (0.1,0.9) \\ \scriptstyle (0.0,1.0)\ \times\ (0.0,1.0) \end{pmatrix} \cdot f_d(b, c) \\
&= \left(\begin{smallmatrix} 0.03 & 0.27 & 0.07 & 0.63 \\ 0.0 & 0.0 & 0.0 & 1.0 \end{smallmatrix}\right) \cdot \begin{bmatrix} 0.5 & 0.5 \\ 0.0 & 1.0 \\ 0.0 & 1.0 \\ 0.0 & 1.0 \end{bmatrix} = \left(\begin{smallmatrix} 0.015 & 0.985 \\ 0.0 & 1.0 \end{smallmatrix}\right)
\end{aligned}$$

All the results are (2×2)-matrices which in the end have to be multiplied by the original common value $\pi(a_1) = \pi(a_2) = (0.4, 0.6)$:

$$\begin{aligned}
\pi(b) &= (0.4, 0.6) \cdot \left(\begin{smallmatrix} 0.3 & 0.7 \\ 0.0 & 1.0 \end{smallmatrix}\right) = (0.12, 0.88) \\
\pi(c) &= (0.4, 0.6) \cdot \left(\begin{smallmatrix} 0.1 & 0.9 \\ 0.0 & 1.0 \end{smallmatrix}\right) = (0.04, 0.96) \\
\pi(d) &= (0.4, 0.6) \cdot \left(\begin{smallmatrix} 0.015 & 0.985 \\ 0.0 & 1.0 \end{smallmatrix}\right) = (0.006, 0.994)
\end{aligned}$$

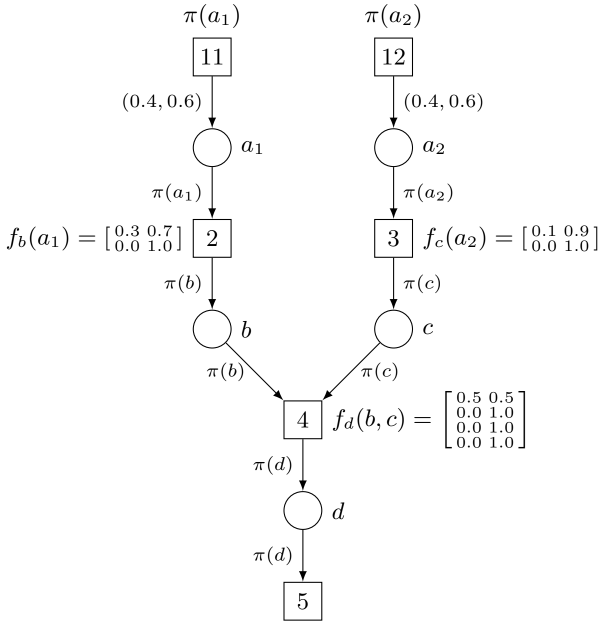


Fig. 2.

3 Medical Diagnostics

There are abductive approaches for solving diagnostic approaches since the 70s. Nevertheless, we consider it worthwhile to add a Petri net approach on the basis of probability propagation nets (PPNs) [4,5,6,7,8]. As to PPNs, we are influenced by the work on Bayesian networks (BNs), in particular by the work of D. Poole, e.g. *Probabilistic Horn abduction and Bayesian networks* [10], and the books by Pearl and Neapolitan [3,11]. With respect to diagnostics, we are inspired by the book *Abductive Inference Models for Diagnostic Problem-Solving* [1] by Peng and Reggia.

3.1 Probabilistic Causal Model (Peng and Reggia)

Definition 1. (diagnostic problem) *Let* $D = \{d_1, \ldots, d_n\} \neq \emptyset$ *be a finite set of* disorders *(e.g. diseases),*
let $M = \{m_1, \ldots, m_k\} \neq \emptyset$ *be a finite set of* manifestations *(e.g. symptoms) s.t.* $D \cap M = \emptyset$*,*
let $C \subseteq D \times M$ *be a relation where* $(d_i, m_j) \in C$ *means that* "disorder d_i may cause manifestation m_j"*,*
let $M^+ \subseteq M$ *be the subset of* M *that represents the manifestations which are* currently present*;*
then $p = (D, M, C, M^+)$ *is a* diagnostic problem. □

Note that $(d_i, m_j) \in C$ does not mean that d_i necessarily causes m_j, but only that m_j may occur when d_i is present.

Definition 2. (cover, hypothesis) *Let* $p = (D, M, C, M^+)$ *be a diagnostic problem;*

$$\begin{aligned} \textit{effects}(d_i) &:= \{m_j | (d_i, m_j) \in C\} = C(d_i) \textit{ represents the manifestations} \\ &\quad \textit{which are } \text{possible effects of } d_i\textit{;} \\ \textit{causes}(m_j) &:= \{d_i | (d_i, m_j) \in C\} = C^{-1}(m_j) \textit{ represents the disorders} \\ &\quad \textit{which are } \text{possible causes of } m_j\textit{;} \end{aligned}$$

for $D_I \subseteq D$ *and* $M_J \subseteq M$

$$\textit{effects}(D_I) := \bigcup_{d_i \in D_I} \textit{effects}(d_i)$$

$$\textit{causes}(M_J) := \bigcup_{m_j \in M_J} \textit{causes}(m_j)$$

D_I *is a* cover *of* M_J *iff* $M_J \subseteq \textit{effects}(D_I)$*, i.e.* D_I *is a cover of* M_J *iff the disorders of* D_I *may cause all manifestations of* M_J*.*
D_I *is a* hypothesis or explanation *iff* D_I *is a cover of* M^+*.*
D_I *is a* simple or non-redundant *hypothesis iff no proper subset* $D'_I \subsetneqq D_I$ *of* D_I *is also a cover of* M^+*.* ☐

One of the major points of the theory is to clearly distinguish between

$$P(d_i \text{ causes } m_j | d_i) \quad \text{and} \quad P(m_j | d_i) \quad .$$

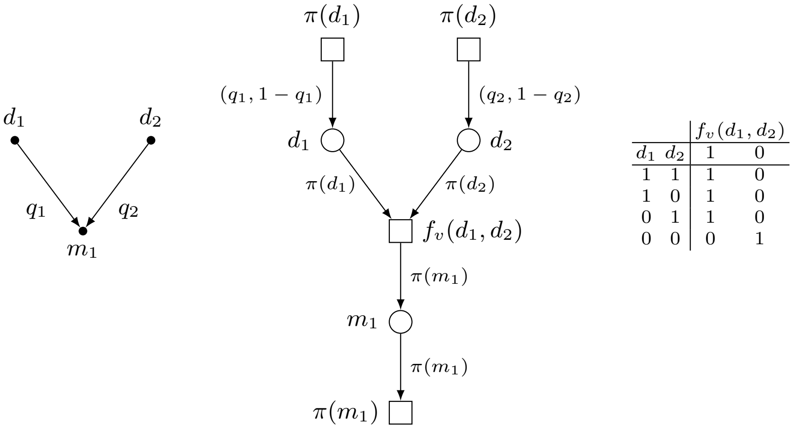
The first is the probability that d_i *really causes* m_j when d_i is present; the second is the probability that m_j *occurs* when d_i is present.

Definition 3. (causal strength) *Let* $p = (D, M, C, M^+)$ *be a diagnostic problem; let be* $(d_i, m_j) \in D \times M$*, then the* causal strength c_{ij} of (d_i, m_j) *is defined as*

$$c_{ij} := \begin{cases} 0 & \text{if } (d_i, m_j) \notin C \\ P(d_i \text{ causes } m_j | d_i) \in (0, 1] & \text{if } (d_i, m_j) \in C \end{cases} \quad .$$

☐

It is important to know that $c_{ij} \neq P(m_j | d_i)$. This is obvious for $(d_i, m_j) \notin C$. In this case $c_{ij} = 0$ holds, but $P(m_j | d_i) > 0$ might hold when d_i is present but m_j is caused by some $d_k \neq d_i$ with $(d_k, m_j) \in C$.



		$f_v(d_1,d_2)$	
d_1	d_2	1	0
1	1	1	0
1	0	1	0
0	1	1	0
0	0	0	1

(a) **(b)** **(c)**

Fig. 3.

3.2 Transformation of a Diagnostic Problem into a Bayesian Model

In the following it will be important that the causal strengths are *invariant*. So we assume that the disorders of D are *independent* of each other.

Let now (D, M, C, M^+) be a diagnostic problem with one manifestation and a finite number of disorders: $M = \{m_1\}$, $D = \{d_1, \ldots, d_n\}$.

For describing the method we assume $n = 2$. This is no real limitation of the general case $n \geqq 2$ because of the independency of the $d_i \in D$. Then the graph of Fig. 3(a) characterizes the diagnostic problem where $c_{11} = q_1$, $c_{21} = q_2$.

For constructing the conditional dependency matrix $f_{m_1}(d_1, d_2) = P(m_1|d_1d_2)$ (i.e. $D_I = \{d_1, d_2\}$) we use the PPN of Fig. 3(b). Since m_1 may be caused by d_1 *or* d_2 we have to deal with four cases. The general formula for $\pi(m_1)$ is $\pi(m_1) = (\pi(d_1) \times \pi(d_2)) \cdot f_v(d_1, d_2)$, where $f_v(d_1, d_2)$ is the name of the (shared) transition in Fig. 3(b) and also the name of the matrix of Fig. 3(c) which corresponds to d_1 *or* d_2.

1st case: d_1 and d_2 are present

$$
\begin{aligned}
\pi(m_1) &= (\pi(d_1) \times \pi(d_2)) \cdot f_v(d_1, d_2) \\
&= ((q_1, (1-q_1)) \times (q_2, (1-q_2))) \cdot f_v(d_1, d_2) \\
&= ((q_1q_2, q_1(1-q_2), (1-q_1)q_2, (1-q_1)(1-q_2))) \cdot f_v(d_1, d_2) \\
&= (q_1q_2, (q_1 - q_1q_2), (q_2 - q_1q_2), (1-q_1)(1-q_2)) \cdot f_v(d_1, d_2) \\
&= ((q_1q_2 + q_1 - q_1q_2 + q_2 - q_1q_2), (1-q_1)(1-q_2)) \\
&= \underline{(q_1 + q_2 - q_1q_2, (1-q_1)(1-q_2))}
\end{aligned}
$$

2nd case: d_1 is present, d_2 is not

$$\begin{aligned}\pi(m_1) &= (\pi(d_1) \times \pi(d_2)) \cdot f_v(d_1, d_2)\\ &= ((q_1, (1 - q_1)) \times (0, 1)) \cdot f_v(d_1, d_2)\\ &= (0, q_1, 0, (1 - q_1)) \cdot f_v(d_1, d_2)\\ &= \underline{(q_1, (1 - q_1))}\end{aligned}$$

3rd case: d_2 is present, d_1 is not

$$\begin{aligned}\pi(m_1) &= (\pi(d_1) \times \pi(d_2)) \cdot f_v(d_1, d_2)\\ &= ((0, 1) \times (q_2, (1 - q_2))) \cdot f_v(d_1, d_2)\\ &= (0, 0, q_2, (1 - q_2)) \cdot f_v(d_1, d_2)\\ &= \underline{(q_2, (1 - q_2))}\end{aligned}$$

4th case: d_1 and d_2 are not present

$$\begin{aligned}\pi(m_1) &= (\pi(d_1) \times \pi(d_2)) \cdot f_v(d_1, d_2)\\ &= ((0, 1) \times (0, 1)) \cdot f_v(d_1, d_2)\\ &= (0, 0, 0, 1) \cdot f_v(d_1, d_2)\\ &= \underline{(0, 1)}\end{aligned}$$

Now the matrix $P(m_1|d_1 d_2)$ can be built:

		m_1		
d_1	d_2	1	0	
1	1	$q_1 + q_2 - q_1 q_2$	$(1 - q_1)(1 - q_2)$	$D' = \{d_1, d_2\}$
1	0	q_1	$(1 - q_1)$	$D' = \{d_1\}$
0	1	q_2	$(1 - q_2)$	$D' = \{d_2\}$
0	0	0	1	$D' = \emptyset$

The general form of this result is the following theorem.

Theorem 1. (Peng and Reggia, 1986) *Let be (D, M, C, M^+) a diagnostic problem; $m_j \in D$ a manifestation, $D' \subseteq$ causes(m_j); then*

$$P(\neg m_j | \underset{d_i \,\in\, D}{\forall d_i} \;\wedge\; \underset{d_i \,\in\, causes(m_j) \setminus D'}{\forall \neg d_i}) = \prod_{d_i \,\in\, D'} (1 - c_{ij})$$

where $\neg m_j$ and $\neg d_i$ mean that m_j and d_i are not present, respectively. □

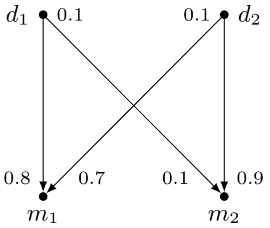


Fig. 4.

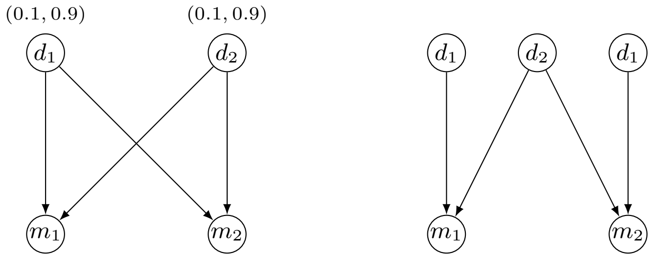
$f_{m_1}(d_1,d_2)$		m_1	
d_1	d_2	1	0
1	1	0.94	0.06
1	0	$\boxed{0.8}$	0.2
0	1	$\boxed{0.7}$	0.3
0	0	0.0	1.0

(a)

$f_{m_2}(d_1,d_2)$		m_1	
d_1	d_2	1	0
1	1	0.91	0.09
1	0	$\boxed{0.1}$	0.9
0	1	$\boxed{0.9}$	0.1
0	0	0.0	1.0

(b)

Fig. 5.



(a) **(b)**

Fig. 6.

3.3 Example (Peng and Reggia 1990)

A diagnostic problem (D, M, C, M^+) is given by the graph of Fig. 4 with $D = \{d_1, d_2\}$, $M = M^+ = \{d_1, d_2\}$, $C = \{(d_1, m_1), (d_1, m_2), (d_2, m_1), (d_2, m_2)\}$, $c_{11} = 0.8$, $c_{21} = 0.7$, $c_{12} = 0.1$, $c_{22} = 0.9$, $P(d_1) = P(d_2) = 0.1$.

The corresponding conditional probability matrices $P(m_1|d_1d_2) = f_{m_1}(d_1d_2)$ and $P_{m_2}(d_1, d_2) = f_{m_2}(d_1, d_2)$ are shown in Fig. 5.

Even though we do not need the BN corresponding to the diagnostic problem of Fig. 4, we show it in Fig. 6(a) to clarify the difference. Note that the matrices of Fig. 5 are parts of the BN. Because the BN is loopy, one of the nodes d_1 *or* d_2 will be cut into two nodes (d_1 in Fig. 6(b)).

We now switch to the PPN of Fig. 7 (that corresponds to the BN of Fig. 6(b)). The matrices attached to the f-transitions have the same names. The first problem to solve is *to calculate* $P(d_2|m_1)$.

For doing so we choose a t-invariant (see Fig. 10) with $\lambda(m_1)$ as input and $\lambda(d_2)$ as output transition. The two copies of transition $\pi(d_1)$ are the result of cutting off the original transition in order to get rid of the cycle (see Fig. 6). Instead of running through the net twice for $\pi(d_i) = (1, 0)$ and $\pi(d_1) = (0, 1)$, we "fold" both runs into one for $\pi(d_1) = \left(\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix}\right)$. This results in matrices $\left(\begin{smallmatrix} 1 & 0 \\ 1 & 0 \end{smallmatrix}\right)$ and $\left(\begin{smallmatrix} 1 & 1 \\ 1 & 1 \end{smallmatrix}\right)$ for $\lambda(m_1)$ and $\lambda(m_2)$, respectively. These values indicate that m_1 is definitely present and that we have no information about m_2.

After two transitions $\pi(d_1)$ and $\lambda(m_1)$ have fired the marking is M_1 with

$$M_1(p) = \begin{cases} \left(\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix}\right) & \text{for } p = d_1 \text{ (twice)} \\ \left(\begin{smallmatrix} 1 & 0 \\ 1 & 0 \end{smallmatrix}\right) & \text{for } p = m_1 \\ \left(\begin{smallmatrix} 1 & 1 \\ 1 & 1 \end{smallmatrix}\right) & \text{for } p = m_2 \\ \text{empty} & \text{for all other places } p \end{cases}$$

When firing $f_{d_2}(d_1, m_2)$ the marking of d_2 is calculated as follows:

$$\begin{aligned} &\left(\left(\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix}\right) \otimes \left(\begin{smallmatrix} 1 & 1 \\ 1 & 1 \end{smallmatrix}\right)\right) \cdot f_{d_2}(d_1, m_2) \\ &= \begin{pmatrix} \scriptstyle (1,0) \times (1,1) \\ \scriptstyle (0,1) \times (1,1) \end{pmatrix} \cdot f_{d_2}(d_1, m_2) \\ &= \left(\begin{smallmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{smallmatrix}\right) \cdot \begin{bmatrix} 0.91 & 0.1 \\ 0.09 & 0.9 \\ 0.9 & 0.0 \\ 0.1 & 1.0 \end{bmatrix} \\ &= \left(\begin{smallmatrix} 1 & 1 \\ 1 & 1 \end{smallmatrix}\right) \end{aligned}$$

Then the marking is M_2 with

$$M_2(p) = \begin{cases} \left(\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix}\right) & \text{for } p = d_1 \\ \left(\begin{smallmatrix} 1 & 0 \\ 1 & 0 \end{smallmatrix}\right) & \text{for } p = m_1 \\ \left(\begin{smallmatrix} 1 & 1 \\ 1 & 1 \end{smallmatrix}\right) & \text{for } p = d_2 \\ \text{empty} & \text{for all other places } p \end{cases}$$

Firing of $f_{d_2}(d_1, m_1)$ yields

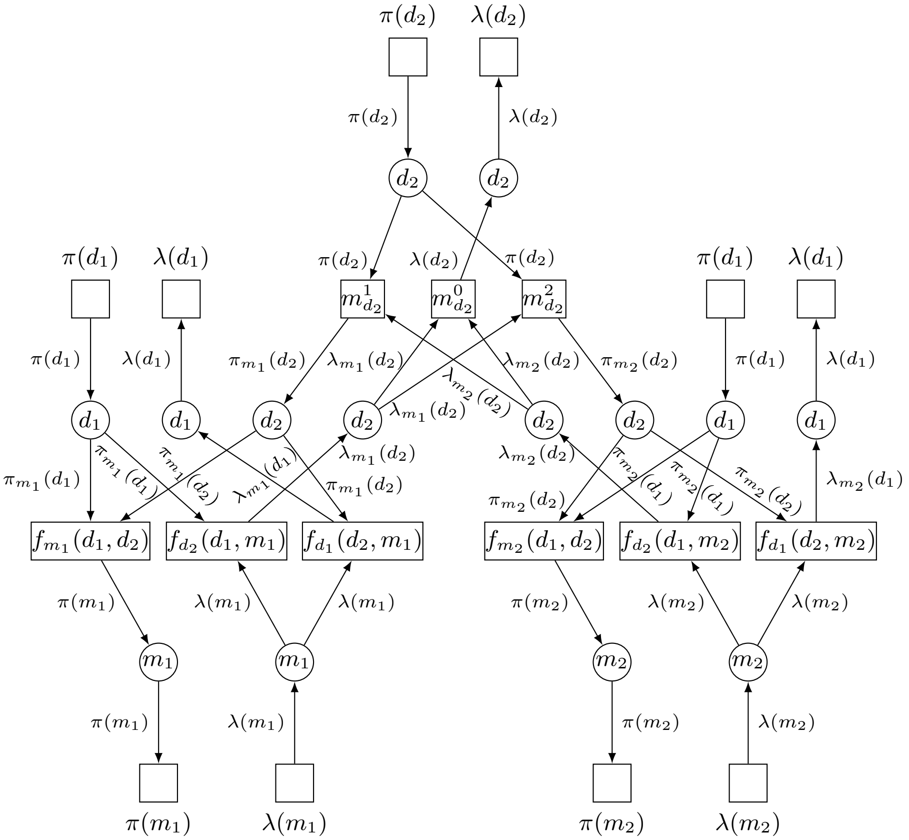


Fig. 7.

		$f_{m_1}(d_1, d_2)$	
d_1	d_2	1	0
1	1	0.94	0.06
1	0	0.8	0.2
0	1	0.7	0.3
0	0	0.0	1.0

		$f_{d_2}(d_1, m_1)$	
d_1	m_1	1	0
1	1	0.94	0.8
1	0	0.06	0.2
0	1	0.7	0.0
0	0	0.3	1.0

		$f_{d_1}(d_2, m_1)$	
d_2	m_1	1	0
1	1	0.94	0.7
1	0	0.06	0.3
0	1	0.8	0.0
0	0	0.2	1.0

Fig. 8.

		$f_{m_2}(d_1, d_2)$	
d_1	d_2	1	0
1	1	0.91	0.09
1	0	0.1	0.9
0	1	0.9	0.1
0	0	0.0	1.0

		$f_{d_2}(d_1, m_2)$	
d_1	m_2	1	0
1	1	0.91	0.1
1	0	0.09	0.9
0	1	0.9	0.0
0	0	0.1	1.0

		$f_{d_1}(d_2, m_2)$	
d_2	m_2	1	0
1	1	0.91	0.9
1	0	0.09	0.1
0	1	0.1	0.0
0	0	0.9	1.0

Fig. 9.

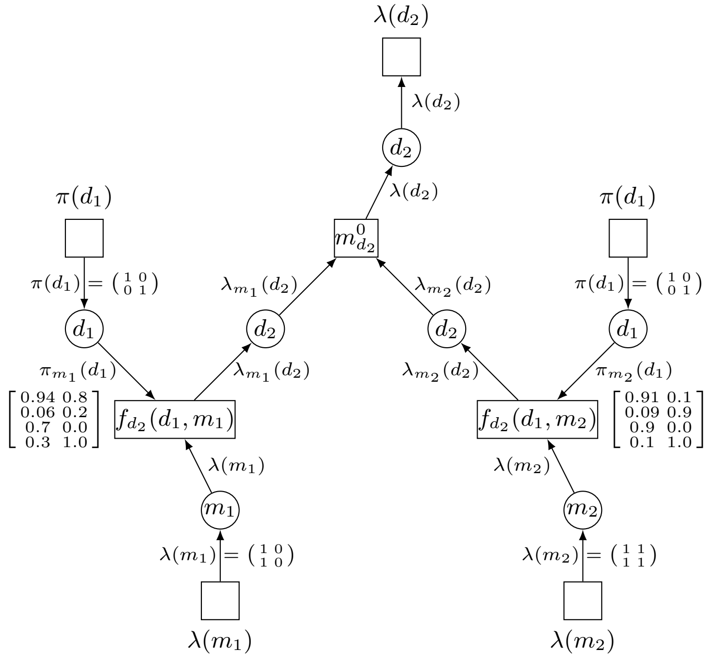


Fig. 10.

$$\begin{aligned}&((\begin{smallmatrix}1&0\\0&1\end{smallmatrix}) \otimes (\begin{smallmatrix}1&0\\1&0\end{smallmatrix})) \cdot f_{d_2}(d_1,m_1)\\ &= \begin{pmatrix}(1,0)\times(1,0)\\(0,1)\times(1,0)\end{pmatrix} \cdot f_{d_2}(d_1,m_1)\\ &= (\begin{smallmatrix}1&0&0&0\\0&0&1&0\end{smallmatrix}) \cdot \begin{bmatrix}0.94&0.8\\0.06&0.2\\0.7&0.0\\0.3&1.0\end{bmatrix}\\ &= (\begin{smallmatrix}0.94&0.8\\0.7&0.0\end{smallmatrix})\end{aligned}$$

Now the marking is M_3 with

$$M_3(p) = \begin{cases}(\begin{smallmatrix}0.94&0.8\\0.7&0.0\end{smallmatrix}) & \text{for } p = d_2\\ (\begin{smallmatrix}1&1\\1&1\end{smallmatrix}) & \text{for } p = d_2\\ \text{empty} & \text{for all other places } p\end{cases}$$

Finally, after firing of $m^0_{d_2}$, under the marking M_4 only d_2 is marked by

$$\begin{aligned}M_4(d_2) &= (\begin{smallmatrix}0.94&0.8\\0.7&0.0\end{smallmatrix}) \circledcirc (\begin{smallmatrix}1&1\\1&1\end{smallmatrix})\\ &= \begin{pmatrix}(0.94,0.8)\circ(1,1)\\(0.7,0.0)\circ(1,1)\end{pmatrix}\\ &= (\begin{smallmatrix}0.94&0.8\\0.7&0.0\end{smallmatrix})\end{aligned}$$

To complete the conditioning process, this matrix has to be multiplied with the prior probability of d_2:

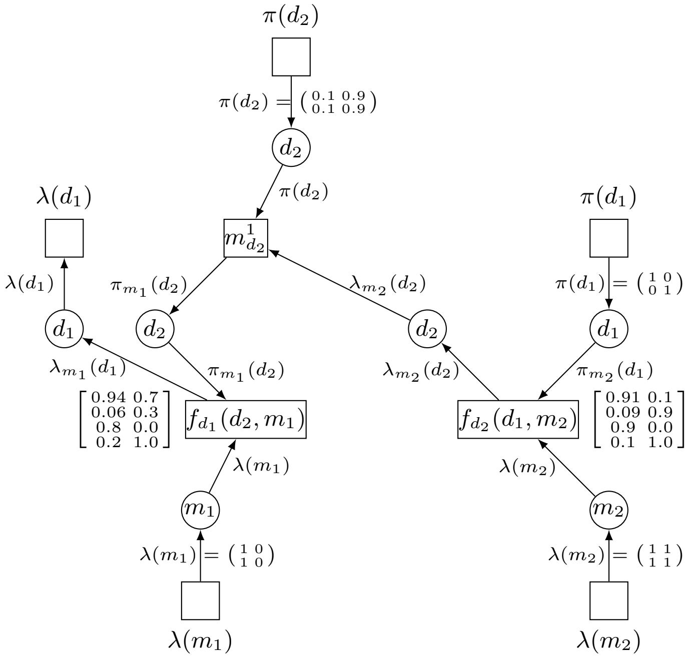


Fig. 11.

$$\lambda(d_2) = (0.1, 0.9) \cdot \begin{pmatrix} 0.94 & 0.8 \\ 0.7 & 0.0 \end{pmatrix} = (0.724, 0.08)$$

Then the new belief is

$$\begin{aligned} bel(d_2|m_1) &= \alpha \cdot (\pi(d_2) \circ \lambda(d_2)) \\ &= \alpha \cdot ((0.1, 0.9) \circ (0.724, 0.08)) \\ &= \alpha \cdot (0.0724, 0.072) \\ &= \tfrac{1}{0.1444} \cdot (0.0724, 0.072) \\ &= (0.5014, 0.4986) \end{aligned}$$

The next problem is *to calculate* $P(d_1|m_1)$.

Again, we select a t-invariant (Fig. 11) with transitions $\lambda(m_1)$ as input transition (since m_1 might cause d_1) and $\lambda(d_1)$ as output transition (since d_1 might be caused by m_1). $\pi(d_1)$ was cut off, the corresponding arc label is $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ as the result of "folding" the runs for $\pi(d_1) = (1, 0)$ and $\pi(d_1) = (0, 1)$. Consequently, the other arc labels are matrices, too. $\lambda(m_2) = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$ indicates that there is no information about m_2, $\lambda(m_1) = \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix}$ says that m_1 is assumed to be present. $\pi(d_2) = \begin{pmatrix} 0.1 & 0.9 \\ 0.1 & 0.9 \end{pmatrix}$ is to provide the prior probabilities of d_2.

The firing sequence

$$(\pi(d_1), \pi(d_2), \lambda(m_1), \lambda(m_2), f_{d_2}(d_1, m_2), m^1_{d_2}, f_{d_1}(d_2, m_1))$$

yields $\lambda_{m_1}(d_1) = \left(\begin{smallmatrix} 0.814 & 0.07 \\ 0.814 & 0.07 \end{smallmatrix}\right)$. In completing the conditioning we have to calculate

$$\lambda(d_1) = (0.1, 0.9) \cdot \left(\begin{smallmatrix} 0.814 & 0.07 \\ 0.814 & 0.07 \end{smallmatrix}\right) = (0.814, 0.07)$$

(not normalized). The new belief is

$$\begin{aligned} \mathit{bel}(d_1|m_1) &= \alpha \cdot (\pi(d_1) \circ \lambda(d_1)) \\ &= \alpha \cdot ((0.1, 0.9) \circ (0.814, 0.07)) \\ &= \alpha \cdot (0.0814, 0.063) \\ &= \tfrac{1}{0.0814+0.063} \cdot (0.0814, 0.063) \\ &= (0.5637, 0.4363) \end{aligned}$$

The problem *to calculate* $P(d_2|m_1 \textit{ and } m_2)$ seems to be more complex. But this is not the case because we can use the t-invariant of Fig. 10 if we replace the arc label $\lambda(m_2) = \left(\begin{smallmatrix} 1 & 1 \\ 1 & 1 \end{smallmatrix}\right)$ by $\left(\begin{smallmatrix} 1 & 0 \\ 1 & 0 \end{smallmatrix}\right)$, indicating thus that besides m_1 now m_2 is also present.

The firing sequence

$$(\pi(d_1), \pi(d_1), \lambda(m_1), \lambda(m_2), f_{d_2}(d_1, m_1), f_{d_2}(d_1, m_2), m^0_{d_2})$$

yields $\lambda(d_2) = \left(\begin{smallmatrix} 0.8554 & 0.08 \\ 0.63 & 0.0 \end{smallmatrix}\right)$. The conditioning is completed by calculating

$$\lambda(d_1) = (0.1, 0.9) \cdot \left(\begin{smallmatrix} 0.8554 & 0.08 \\ 0.63 & 0.0 \end{smallmatrix}\right) = (0.65254, 0.008)$$

(not normalized). Then

$$\begin{aligned} \mathit{bel}(d_2|m_1 \textit{ and } m_2) &= \alpha(\pi(d_1) \circ \lambda(d_1)) \\ &= \alpha \cdot ((0.1, 0.9) \circ (0.65254, 0.008)) \\ &= \alpha \cdot (0.065254, 0.0072) \\ &= \tfrac{1}{0.065254+0.0072} \cdot (0.065254, 0.0072) \\ &= (0.9006, 0.0994) \end{aligned}$$

Similarly, $P(d_1|m_1 \textit{ and } m_2)$ *can be calculated* by the t-invariant of Fig. 11 after replacing $\lambda(m_2) = \left(\begin{smallmatrix} 1 & 1 \\ 1 & 1 \end{smallmatrix}\right)$ by $\left(\begin{smallmatrix} 1 & 0 \\ 1 & 0 \end{smallmatrix}\right)$. The result is

$$\mathit{bel}(d_1|m_1 \textit{ and } m_2) = (0.2174, 0.7826)$$

4 Operational Risk

Recently, Bayes-based methods were successfully applied to ascertain risks of quite different sorts, as for instance product risks, software product risks, system risks etc. Financial scandals in the banking industry attracted notice of a broad public. In most of these cases the serious losses were due to operational risk in the financial institutions and not to credit or market risk. In the following, we deal with the calculation of losses caused by operational risk and ask for the main causes. Our example is borrowed from the paper "Operational Risk and Probabilistic Networks – An Application to Corporate Actions Processing" [2].

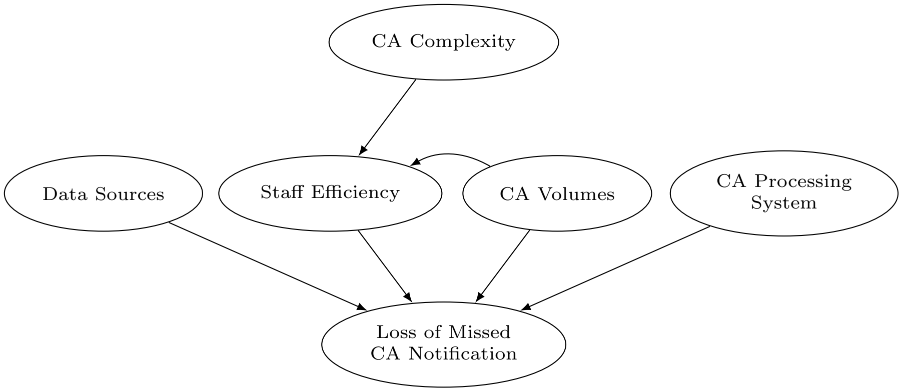


Fig. 12. BN for a Missed CA Announcement

4.1 Calculation of Loss Probabilities

We start off with the BN of Fig. 12. The random variables can shortly be explained as follows.

Data Sources. Data sources can be registrars, custodians, data vendors etc. who provide corporate action announcement data.

Corporate Action Volumes. Corporate actions are announced every year on equity and debt instruments.

Corporate Action Type Complexity. In general, voluntary corporate actions and mandatory actions are considered to be more complex than mandatory actions.

Corporate Action Processing System. The amount of automation in corporate action processing that varies amongst organizers and heterogeneous platforms may cause chaos.

Staff Efficiency. A low or unsufficient staff efficiency may cause extreme losses.

Loss of Missed Corporate Action Announcement. The loss due to Corporate Action Announcement indicates the evidence of operational loss.

The BN of Fig. 12 contains a cycle that is eliminated by cutting off the node *CA Volumes* in the course of the conditioning technique. This is reflected in the DN of Fig. 13.

The prior probabilities and the conditional probability matrices are given as follows.

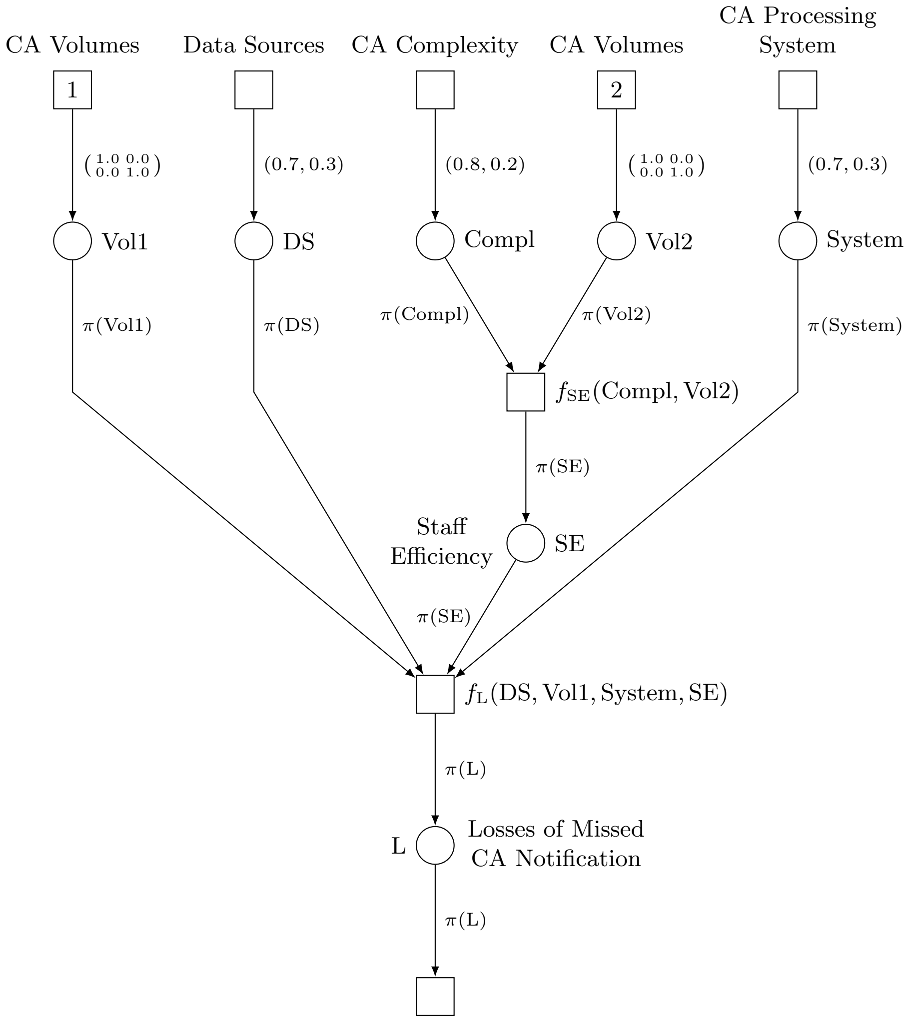


Fig. 13. Dependency Net

	good	bad
Data Sources	0.7	0.3

	low	high
CA Volumes	0.3	0.7

	low	high
CA Complexity	0.8	0.2

	good	bad
CA Processing System	0.7	0.3

The conditional probability matrix for the *Staff Efficiency* is:

$$P(\mathrm{SE} \mid \mathrm{Compl}, \mathrm{Vol2}) = f_{\mathrm{SE}}(\mathrm{Compl}, \mathrm{Vol2}) = \begin{array}{cc|ll} & & \multicolumn{2}{c}{\mathrm{SE}} \\ \hline \mathrm{Compl} & \mathrm{Vol2} & \mathrm{low} & \mathrm{high} \\ \hline \mathrm{low} & \mathrm{low} & 0.25 & 0.75 \\ \mathrm{low} & \mathrm{high} & 0.4 & 0.6 \\ \mathrm{high} & \mathrm{low} & 0.4 & 0.6 \\ \mathrm{high} & \mathrm{high} & 0.55 & 0.45 \end{array}$$

The conditional probability matrix for the *Loss of Mixed CA Notification* is shown in Table 1.

The calculation of $\boldsymbol{\pi}$(SE)

$$\begin{aligned} & (\pi(\mathrm{Compl}) \times \pi(\mathrm{Vol2})) \cdot f_{\mathrm{SE}}(\mathrm{Compl}, \mathrm{Vol2}) \\ = & ((0.8, 0.2) \times \left(\begin{smallmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{smallmatrix}\right)) \cdot f_{\mathrm{SE}}(\mathrm{Compl}, \mathrm{Vol2}) \\ = & \left(\begin{smallmatrix} 0.8 & 0.0 & 0.2 & 0.0 \\ 0.0 & 0.8 & 0.0 & 0.2 \end{smallmatrix}\right) \cdot \left[\begin{smallmatrix} 0.25 & 0.75 \\ 0.4 & 0.6 \\ 0.4 & 0.6 \\ 0.55 & 0.45 \end{smallmatrix}\right] = \left(\begin{smallmatrix} 0.28 & 0.72 \\ 0.43 & 0.57 \end{smallmatrix}\right) \end{aligned}$$

$$\begin{aligned} \text{So,}\ \ \pi(\mathrm{SE}) &= (0.28, 072) \qquad \text{for } \pi(\mathrm{Vol2}) = (1.0, 0.0) \\ \pi(\mathrm{SE}) &= (0.43, 057) \qquad \text{for } \pi(\mathrm{Vol2}) = (0.0, 1.0) \end{aligned}$$

$$\begin{aligned} \text{and } \pi(\mathrm{SE}) &= 0.3 \cdot (0.28, 0.72) + 0.7 \cdot (0.43, 0.57) \\ &= (0.385, 0.615) \quad \text{for } \pi(\mathrm{Vol2}) = (0.3, 0.7). \end{aligned}$$

In detail: the probability of a low SE is 0.385; the probability of a high SE is 0.615.

The calculation of $\boldsymbol{\pi}$(Loss)

$$\begin{aligned} & (\pi(\mathrm{DS}) \times \pi(\mathrm{Vol1}) \times \pi(\mathrm{System}) \times \pi(\mathrm{SE})) \cdot f_{\mathrm{L}}(\mathrm{DS}, \mathrm{Vol1}, \mathrm{System}, \mathrm{SE}) \\ = & ((0.7, 0.3) \times \left(\begin{smallmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{smallmatrix}\right) \times (0.7, 0.3) \times \left(\begin{smallmatrix} 0.28 & 0.72 \\ 0.43 & 0.57 \end{smallmatrix}\right)) \cdot f_{\mathrm{L}}(\mathrm{DS}, \mathrm{Vol1}, \mathrm{System}, \mathrm{SE}) \\ = & \left(\begin{smallmatrix} 0.446 & 0.366 & 0.188 \\ 0.320 & 0.456 & 0.224 \end{smallmatrix}\right) \end{aligned}$$

				L Loss of Missed CA Notification		
DS Data Sources	Vol1 CA Volumes	System CA Process. System	SE Staff Efficiency	0-1 million	1-2 million	2-3 million
good	low	good	low	0.5	0.3	0.2
good	low	good	high	0.6	0.3	0.1
good	low	bad	low	0.3	0.4	0.3
good	low	bad	high	0.5	0.4	0.1
good	high	good	low	0.4	0.4	0.2
good	high	good	high	0.5	0.4	0.1
good	high	bad	low	0.2	0.5	0.3
good	high	bad	high	0.3	0.5	0.2
bad	low	good	low	0.2	0.5	0.3
bad	low	good	high	0.3	0.4	0.3
bad	low	bad	low	0.1	0.5	0.4
bad	low	bad	high	0.2	0.5	0.3
bad	high	good	low	0.1	0.6	0.3
bad	high	good	high	0.2	0.5	0.3
bad	high	bad	low	0.1	0.4	0.5
bad	high	bad	high	0.1	0.5	0.4

Table 1. $P(\mathrm{L} \mid \mathrm{DS}, \mathrm{Vol1}, \mathrm{System}, \mathrm{SE}) = f_{\mathrm{L}}(\mathrm{DS}, \mathrm{Vol1}, \mathrm{System}, \mathrm{SE})$

$$\begin{aligned} \text{So, } \quad \pi(\mathrm{L}) &= (0.446, 0.366, 0.188) \quad \text{for } \pi(\mathrm{Vol1}) = (1.0, 0.0) \\ \pi(\mathrm{L}) &= (0.320, 0.456, 0.224) \quad \text{for } \pi(\mathrm{Vol1}) = (0.0, 1.0) \end{aligned}$$

$$\begin{aligned} \text{and } \pi(\mathrm{L}) &= 0.3 \cdot (0.446, 0.366, 0.188) + 0.7 \cdot (0.320, 0.456, 0.224) \\ &= (0.358, 0.429, 0.213) \quad \text{for } \pi(\mathrm{Vol1}) = (0.3, 0.7) \end{aligned}$$

In detail:

the probability of a loss of 0-1 million is 0.358,
of a loss of 1-2 million is 0.429,
of a loss of 2-3 million is 0.213.

4.2 Evidence Propagation

Supposed the operations manager is interested in knowing which one of the influencing factors has the maximum impact on the operational losses. He then could input the best conceivable and derivable result, namely the losses:

0-1 million with probability 1.0
1-2 million with probability 0.0
2-3 million with probability 0.0

Then the beliefs for the input variables are:

Data Sources	good	bad	originally	good	bad
	0.857	0.143		0.7	0.3
CA Volumes	low	high		low	high
	0.374	0.626		0.3	0.7
CA Complexity	low	high		low	high
	0.807	0.193		0.8	0.2
CA Processing System	good	bad		good	bad
	0.786	0.214		0.7	0.3

This shows that obviously the Data Sources have the maximum impact on getting low losses.

We will only demonstrate the calculation of the belief of Data Sources because all the other calculations are quite similar. We will do without drawing the whole PPN and only show the net representation of the t-invariant for calculating $\lambda(\mathrm{DS})$ in Fig. 14. Because the net representation of the t-invariant in Fig. 14 has no cycles there is no need for conditioning and thus for cutting off any transition. The matrix $f_{\mathrm{DS}}(\mathrm{L}, \mathrm{Vol}, \mathrm{System}, \mathrm{SE})$, which is the generalized transposed of $f_{\mathrm{L}}(\mathrm{DS}, \mathrm{Vol}, \mathrm{System}, \mathrm{SE})$ we need, is shown in Table 2.

The calculation of λ(DS)

$$
\begin{aligned}
\lambda(\mathrm{DS}) &= (\lambda(\mathrm{L}) \times \pi(\mathrm{Vol}) \times \pi(\mathrm{System}) \times \pi(\mathrm{SE})) \cdot f_{\mathrm{DS}}(\mathrm{L}, \mathrm{Vol}, \mathrm{System}, \mathrm{SE}) \\
&= ((1.0, 0.0, 0.0) \times (0.3, 0.7) \times (0.7, 0.3) \times (0.385, 0.615)) \\
&\quad \cdot f_{\mathrm{DS}}(\mathrm{L}, \mathrm{Vol}, \mathrm{System}, \mathrm{SE}) \\
&= (0.437, 0.1696)
\end{aligned}
$$

$$
\begin{aligned}
bel(\mathrm{DS}) &= \alpha(\pi(\mathrm{DS}) \circ \lambda(\mathrm{DS})) \\
&= \alpha((0.7, 0.3) \circ (0.437, 0.1696)) \\
&= \alpha(0.3059, 0.05088) \\
&= \tfrac{1}{0.3059+0.05088} \cdot (0.3059, 0.05088) \\
&= (0.857, 0.143)
\end{aligned}
$$

So, the operations manager is well advised first of all to increase the quality of Data Sources in order to considerably reduce the losses.

5 Conclusion and Outlook

We have demonstrated by two adequate examples how to work with PPNs. On the basis of our experience with PPNs we are convinced that it is about time to build a suitable tool.

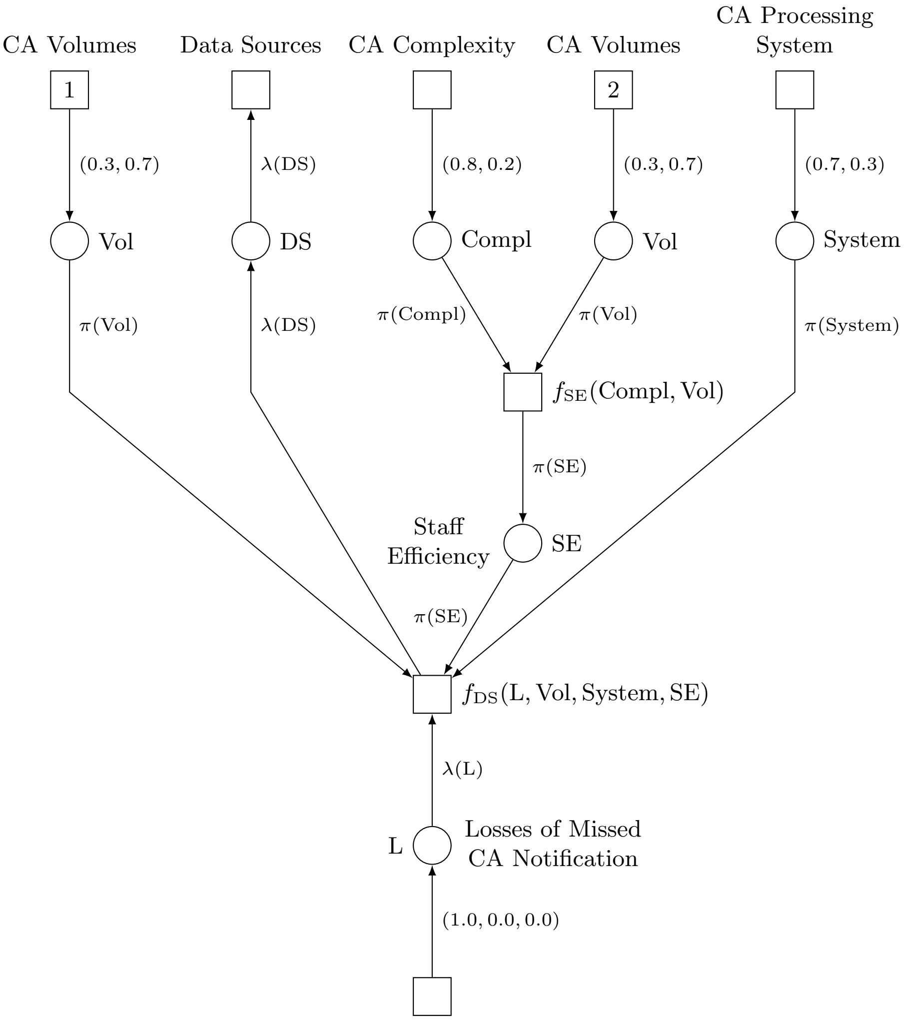

CA Volumes
Data Sources
CA Complexity
CA Volumes
CA Processing System
1
2
(0.3, 0.7)
λ(DS)
(0.8, 0.2)
(0.3, 0.7)
(0.7, 0.3)
Vol
DS
Compl
Vol
System
π(Vol)
λ(DS)
π(Compl)
π(Vol)
π(System)
f_SE(Compl, Vol)
π(SE)
Staff Efficiency
SE
π(SE)
f_DS(L, Vol, System, SE)
λ(L)
L
Losses of Missed CA Notification
(1.0, 0.0, 0.0)

Fig. 14.

				DS Data Sources	
L Loss	Vol CA Volumes	System CA Process. System	SE Staff Efficiency	good	bad
0-1	low	good	low	0.5	0.2
0-1	low	good	high	0.6	0.3
0-1	low	bad	low	0.3	0.1
0-1	low	bad	high	0.5	0.2
0-1	high	good	low	0.4	0.1
0-1	high	good	high	0.5	0.2
0-1	high	bad	low	0.2	0.1
0-1	high	bad	high	0.3	0.1
1-2	low	good	low	0.3	0.5
1-2	low	good	high	0.3	0.4
1-2	low	bad	low	0.4	0.5
1-2	low	bad	high	0.4	0.5
1-2	high	good	low	0.4	0.6
1-2	high	good	high	0.4	0.5
1-2	high	bad	low	0.5	0.4
1-2	high	bad	high	0.5	0.5
2-3	low	good	low	0.2	0.3
2-3	low	good	high	0.1	0.3
2-3	low	bad	low	0.3	0.4
2-3	low	bad	high	0.1	0.3
2-3	high	good	low	0.2	0.3
2-3	high	good	high	0.1	0.3
2-3	high	bad	low	0.3	0.5
2-3	high	bad	high	0.2	0.4

Table 2. $P(\mathrm{DS} \mid \mathrm{L}, \mathrm{Vol}, \mathrm{System}, \mathrm{SE}) = f_{\mathrm{DS}}(\mathrm{L}, \mathrm{Vol}, \mathrm{System}, \mathrm{SE})$

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