Translating Workflow Nets to Process Trees: An Algorithmic Approach

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Abstract: Since their introduction, process trees have been frequently used as a process modeling formalism in many process mining algorithms. A process tree is a (mathematical) tree-based model of a process, in which internal vertices represent behavioral control-flow relations and leaves represent process activities. Translation of a process tree into a sound Workflow net is trivial; however, the reverse is not the case. Simultaneously, an algorithm that translates a WF-net into a process tree is of great interest, e.g., the explicit knowledge of the control-flow hierarchy in a WF-net allows one to reason on its behavior more easily. Hence, in this paper, we present such an algorithm, i.e., it detects whether a WF-net corresponds to a process tree, and, if so, constructs it. We prove that, when the algorithm finds a process tree, the language of the process tree is equal to the language of the original WF-net. The experiments conducted show that the algorithm’s corresponding implementation has a quadratic time complexity in the size of the WF-net. Furthermore, the experiments show strong evidence of process tree re-discoverability.

Keywords: process trees; Petri nets; workflow nets; process mining.

1. Introduction

Process mining [1] is concerned with distilling knowledge of the execution of processes by analyzing the event data generated during the execution of these processes, i.e., stored in modern-day information systems. In the field, different (semi-)automated techniques have been developed that allow one to distill processes knowledge from event data, i.e., ranging from automated process discovery algorithms to conformance checking algorithms. In automated process discovery, the main aim is to translate observed process behavior, i.e., as stored in the information system, into a process model that accurately describes the behavior of the process. In this context, the discovered process model should strike an adequate balance between accounting for unobserved, yet likely, process behavior (i.e., avoiding overfitting) and being precise (i.e., avoiding underfitting) at the same time. Conformance checking techniques allow us to compute to what degree the observed behavior is in line with a given reference process model (either designed by hand or discovered using an automated process discovery technique). Since processes are the cornerstone of process mining, so are the models that allow us to represent them (and reason about their behavior and quality). As such, various process modeling formalisms exist, e.g., BPMN [2], EPCs [3], etc., some of which are heavily used in practice.

Recently, process trees were introduced [4]. A process tree is a hierarchical representation of a process corresponding to the mathematical notion of a rooted tree, i.e., a connected undirected acyclic graph with a designated root vertex. The internal vertices of a process tree represent how their children relate to each other regarding their control-flow behavior (i.e., their sequential scheduling). The leaves
of the tree represent the activities of the process. Consider Fig. 3 (page 6), in which we depict an example process tree. Its root vertex has label →, specifying that first its leftmost child, i.e., activity a, needs to be executed, secondly its middle child, and, finally, its rightmost child. Its middle child has a ⊕ label, specifying cyclic behavior, i.e., its leftmost child is always executed, whereas the execution of its rightmost child stipulates that we need to repeat its leftmost child. The ×-label in a process tree represents an exclusive choice, e.g., vertex v1,3 specifies that we either executed activity g or h, yet not both. Finally, the ∧-label refers to concurrency, i.e., the children of a vertex with such a label are allowed to be executed simultaneously, i.e., at the same time. Furthermore, consider the two models depicted in Fig. 1. (page 3). The models represent the same behavior, based on a real-life event log. Clearly, the hierarchy of the process tree allows one to more easily understand the main control-flow of the process.

The previous examples show the relative simplicity at which one can reason on the behavior of a process tree. Furthermore, it is straightforward to translate process trees into other process modeling formalisms, e.g., Workflow nets (WF-nets). By definition, a process tree corresponds to a sound WF-net, i.e., a WF-net with desirable behavioral properties, e.g., the absence of deadlocks. The reverse, i.e., translating a given WF-net into a process tree (if possible), is less trivial. At the same time, obtaining such a translation is of great interest, e.g., it allows us to discover control-flow-aware hierarchical structures within a WF-net. Such structures can, for example, be used to hide certain parts of the model, i.e., leading to a more understandable view of the process model. Furthermore, any algorithm optimized for process trees, e.g., by exploiting the hierarchical structure, can also be applied to WF-nets of such a type. For example, in [8], it is shown that the computation time of alignments [9], i.e., explanations of observed behavior in terms of a reference model, can be significantly reduced by applying Petri net decomposition on the basis of model hierarchies. Hence, computing a process tree representation of the WF-net can be exploited to reduce the computational complexity of the calculations mentioned.

In this paper, we present an algorithm that determines whether a given WF-net corresponds to a process tree, and, if so, constructs it. We prove that, if the algorithm finds a process tree, the original WF-net is sound, and the obtained process tree’s language is equal to the language of the original WF-net. A corresponding implementation, extending the process mining framework PM4Py [10], is publicly available. Using the implementation, we conducted several experiments that show a quadratic time complexity in terms of the WF-net size. Furthermore, our experiments indicate that the algorithm can re-discover process trees, i.e., the process models used to generate the input for the experiments are re-discovered by the algorithm.

The remainder of this paper is structured as follows. In Section 2, we present preliminary concepts and notation. In Section 3, we present the proposed algorithm, including the proofs w.r.t soundness preservation and language preservation. In Section 4, we evaluate our approach. In Section 5, we discuss related work. In Section 6, we discuss various aspects of our approach, e.g., extensibility, in more detail. Section 7, concludes the paper.

2. Preliminaries

In this section, we present basic preliminary notions that ease the readability of this paper. In Section 2.1, we present the basic notation used in this paper. In Section 2.2, we introduce Workflow nets. Finally, in Section 2.3, we present the notion of process trees and their relation to Workflow nets.

2.1. Basic Notation

Given set $X$, $\mathcal{P}(X) = \{X' \subseteq X\}$ denotes its powerset. Given a function $f : X \rightarrow Y$ and $X' \subseteq X$, we extend function application to sets, i.e., $f(X') = \{y \mid \exists x \in X' (f(x) = y)\}$. Furthermore, $f|_{X'} : X' \rightarrow Y$ restricts $f$ to $X'$. A multiset over set $X$, i.e., $m : X \rightarrow \mathbb{N}\cup\{0\}$, contains multiple instances of an element. We write a multiset as $m = [x_1^1, x_2^j, ..., x_k^k]$, where $m(x_1) = i, m(x_2) = j, ..., m(x_n) = k$, for $i, j, ..., k > 1$ (in case, $m(x) = 1$, we omit its superscript; in case $m(x) = 0$, we omit $x$). The set of all multisets over $X$ is written
Figure 1. The same process model, obtained by applying the Inductive Miner [5] implementation of ProM [6] on a real event data set [7], in different process modeling formalisms. Because of its hierarchical nature, the process tree formalism easily allows us to spot the main control-flow behavior.
as $M(X)$. Given $m \in M(X)$, we write $x \in_m m$ if $m(x) > 0$, and, $x \notin_m m$ if $m(x) = 0$, and, $m = \{ x | x \in_m m \}$.

For example, the multiset $[x^2, y]$ consists of two instances of $x$, one instance of $y$, and zero instances of $z$. The sum of two multisets $m_1, m_2$ is written as $m_1 \oplus m_2$, e.g., $[x^2, y] \oplus [x^3, y, z] = [x^5, y^2, z]$. Their difference is written as $m_1 - m_2$, e.g., $[x^2, y] - [x, y, z] = [x]$. A set is considered a multiset in which each element appears only once. Hence, we also apply the operations defined for multisets on sets, and, on combinations of sets and multisets, e.g., $\{ x, y, z \} \oplus [x^2, y, z]$.

A sequence is an ordered collection of elements, e.g., a sequence $\sigma$ of length $n$ over base set $X$ is a function $\sigma: \{ 1, ..., n \} \rightarrow X$. We write $|\sigma|$ to denote the length of $\sigma$, e.g., $|\sigma| = n$. We write $\sigma = (\sigma(1), \sigma(2), ..., \sigma(|\sigma|))$, where $\sigma(i)$ denotes the element at position $i$, $(1 \leq i \leq |\sigma|)$. $e$ denotes the empty sequence, i.e., $|e| = 0$. We extend the notion of element inclusion to sequences, e.g., $x \in (x, y, z)$.

$X^*$ denotes the set of all sequences over members of set $X$. Concatenation of sequences $\sigma, \sigma' \in X^*$ is written as $\sigma \cdot \sigma'$. We let $\sigma = \sigma'$ denote the set of all possible order-preserving merges, i.e., the shuffle operator, of $\sigma$ and $\sigma'$, e.g., given $\sigma_1 = \langle b, p \rangle$, $\sigma_2 = \langle m \rangle$, then $\sigma_1 = \sigma_2 = \{ \langle b, p, m \rangle, \langle b, m, p \rangle, \langle m, b, p \rangle \}$. It is easy to see that $\sigma = \sigma' = \sigma''$ (the operator is commutative). We extend the shuffle operator to sets (and overload notation), i.e., given $S, S' \in X^*$, $S \equiv S' = \{ \sigma \in \sigma_1 \equiv \sigma_2 | \sigma_1 \in S_1 \land \sigma_2 \in S_2 \}$. Note that, $(\sigma = \sigma') = \{ \sigma'' \} = (\sigma = \sigma')$ (associative), hence, we write the application of the shuffle operation on $n$ sequences as $\sigma_1 \equiv \sigma_2 \equiv \cdots \equiv \sigma_n$. Similarly, we write $S_1 \equiv S_2 \equiv \cdots \equiv S_n$ for sets of sequences $S_1, S_2, ..., S_n \in X^*$. Given a function $f: X \rightarrow Y$ and a sequence $\sigma \in X^*$, we overload notation for function application, i.e., $f(\sigma) = (f(\sigma(1)), f(\sigma(2)), ..., f(\sigma(|\sigma|)))$. We extend the notion of sequence application to sets of sequences, i.e., given $f: X \rightarrow Y$ and $X' \subseteq X^*$, $f(X') = \{ \sigma \in X^* | \exists \sigma' \in X' (f(\sigma') = \sigma) \}$. Furthermore, given $X' \subseteq X$ and a sequence $\sigma \in X^*$, we define $\sigma_{|X'}$, where (recursively) $e_{|X'} = e$, $(\langle x \rangle \cdot \sigma)_{|X'} = x \cdot \sigma_{|X'}$, if $x \in X'$ and $(\langle x \rangle \cdot \sigma)_{|X'} = \sigma_{|X'}$ if $x \notin X'$.

### 2.2. Workflow Nets

Workflow nets (WF-nets) [11] extend the more general notion of Petri nets [12]. A Petri net is a directed bipartite graph containing two types of vertices, i.e., places and transitions. We visualize places as circles, whereas we visualize transitions as boxes. Places only connect to transitions and vice-versa.

Consider Fig. 2, depicting an example Petri net (which is also a WF-net). We let $N = (P, T, F, \ell)$ denote a labeled Petri net, where, $P$ denotes a set of places, $T$ denotes a set of transitions and $F \subseteq (P \times T) \cup (T \times P)$ represents the arcs. Furthermore, given a set of labels $\Sigma$ and the symbol $\tau \notin \Sigma$, $\ell: T \rightarrow \Sigma \cup \{ \tau \}$ is the net’s labelling function, e.g., in Fig. 2, $\ell(t_1) = a$, $\ell(t_2) = b$, etc. Given an element $x \in P \cup T$, $x = \{ y | (y, x) \in F \}$ denotes the pre-set of $x$, whereas $x^* = \{ y | (x, y) \in F \}$ denotes its post-set, e.g., in Fig. 2, $x^* = \{ p_1 \}$ and $p_1^* = \{ t_2, t_3 \}$. We lift the $\bullet$ notation to the level of sets, i.e., given $X \subseteq P \cup T$,

- $X = \{ y | \exists x \in X (y \in \bullet x) \}$ and $X^* = \{ y | \exists x \in P (y \in \bullet x) \}$. Let $N = (P, T, F, \ell, \tau)$ be a Petri net and let $P' \subseteq P$, $T' \subseteq T$ and $F' = F \cap ((P' \times T') \cup (T' \times P'))$. The Petri net $N' = (P', T', F', \ell|_{T'})$ is a subnet of $N$, written $N' \subseteq N$. In the context of this paper, we refer to a subnet $N' \subseteq N$ as a fragment if it is weakly connected.
Furthermore, a fragment \(N' \subseteq N\) is place-bordered iff the only vertices of \(N'\) (i.e., members of \(P' \cup T'\)) that are connected to vertices that do not belong to \(N'\) (i.e., members of \(P \cup T'\setminus (P' \cup T')\)) are places, i.e., \(\{x \in P' \cup T' \mid (x,y) \in F' \lor (y,x) \in F'\} \subseteq P'.\) Furthermore, we refer to \(P' = \{x \in P' \mid (x,y) \in F'\}\) and \(P'_o = \{x \in P' \mid (x,y) \in F'\}\) to the input and output places of the place-bordered fragment. For example, in Fig. 2, the subnet formed by places \(p_1, p_2, p_3, p_4, p_5,\) transitions \(t_2, t_3, t_4, t_5\) and the arcs \((p_1, t_2), (p_1, t_3), \ldots, (t_5, p_5)\) is a place-bordered fragment. Observe that, if we remove place \(p_5\) (and the corresponding arc \((t_5, p_5)\)), the subnet is still a fragment, yet, no longer place-bordered. If we also remove \(t_5\) and the arcs \((p_3, t_5)\) and \((p_4, t_5)\), the subnet is not a fragment as it is no longer weakly connected. We let \(N\) denote the universe of Petri nets.

The state of a Petri net is expressed by means of a marking, i.e., a multiset of places. A marking is visualized by drawing the corresponding number of dots in the place(s) of the marking, e.g., the marking in Fig. 2 is \([p]_1\) (one black dot is drawn inside place \(p_j\)). Given a Petri net \(N = (P, T, F, \ell)\) and marking \(M \in M(P)\), \((N, M)\) denotes a marked net. Given a marked net \((N, M),\) a transition \(t \in T\) is enabled, written \((N, M)[t]\), if \(\forall p \in \ell(t)(M(p) > 0).\) If a transition is not enabled in marking \(M\), we write \((N, M)[t]\). An enabled transition can fire, leading to a new marking \(M' = (M \rightarrow \ell(t)) \cup \bullet\), written \((N, M) \rightarrow (N, M')\). A sequence of transition firings \(\sigma = (t_1, t_2, \ldots, t_n)\) is a firing sequence of \((N, M),\) yielding marking \(M',\) written \((N, M) \rightarrow (N, M')\), iff \(\exists M_1, M_2, \ldots, M_{n-1} \in M(P)\) s.t. \((N, M) \rightarrow (N, M_1) \rightarrow (N, M_2) \cdots \rightarrow (N, M_{n-1}) \rightarrow (N, M').\) We write \((N, M) \rightarrow (N, M')\), in case \(\sigma\) is a firing sequence in \((N, M),\) yet, we are not interested in the marking it leads to. In some cases, we simply write \((N, M) \rightarrow (N, M')\), if \(\exists \sigma \in T^+ ((N, M) \rightarrow (N, M')).\)

The language of \(N,\) conditional to markings \(M\) and \(M',\) is defined as \(L_N(N, M, M') = \{\sigma \in T^+ \mid (N, M) \rightarrow (N, M')\}\). Given a Petri net \(N = (P, T, F, \ell)\), and a designated initial and final marking \(M_i, M_f \in M(P),\) the triple \(SN = (N, M_i, M_f)\) denotes a system net. As system net \(SN = (N, M_i, M_f)\) is formed by \(N,\) we write \(SN\) as a replacement for \(N,\) e.g., \((SN, M)\) denotes a marked system net. Clearly, \(R(SN, M)\), \(L_N(SN, M, M'),\) etc., are readily defined for arbitrary markings \(M, M' \in M(P).\) The language of \(SN\) is referred to as \(L_N(SN, M_i, M_f),\) for which we simply write \(L_N(SN)\) (respectively \(L_N(SN), R(SN),\) etc.), i.e., we drop \(M_i\) and \(M_f\) from the notation as they are clear from context. \(SN\) denotes the universe of system nets.

A WF-net is a special type of Petri net, i.e., it has one unique start and one unique end place. Furthermore, every place-transition in the net is on a path from the start to the end place. We formally define a WF-net as follows

**Definition 1** (Labeled Workflow net (WF-net)). Let \(\Sigma\) denote the universe of (activity) labels, let \(\tau \notin \Sigma\) and let \(\ell : T \rightarrow \Sigma \cup \{\tau\}.\) Let \(N = (P, T, F, \ell) \in \mathcal{N}\) and let \(p_i \neq p_o \in P.\) Tuple \(W = (P, T, F, p_i, p_o, \ell)\) is a Workflow net (WF-net), iff:

1. \(p_i = \emptyset \lor \exists p \in P \setminus\{p_i\} (p = \emptyset); p_i\) is the unique source place.
2. \(p_o = \emptyset \lor \exists p \in P \setminus\{p_o\} (p = \emptyset); p_o\) is the unique sink place.
3. Each element \(x \in P \cup T\) is on a path from \(p_i\) to \(p_o.\)

We let \(W\) denote the universe of WF-nets.

Observe that, a WF-net is a system net with \(M_i = [p_i]\) and \(M_f = [p_o]\) Hence, since a WF-net is formed by an underlying Petri net, and, has a well-defined initial and final marking, i.e., \([p_i]\) and \([p_o]\), we write \(L_N(W)\) (respectively \(L_N(W), R(W),\) etc.) as a shorthand notation for \(L_N(W, [p_i], [p_o]).\)

Of particular interest are sound WF-nets, i.e., WF-nets that are guaranteed to be free of deadlocks, livelocks and dead transitions. We formalize the notion of soundness as follows.
Definition 2 (Soundness). Let \( W = (P, T, F, p_i, p_o, \ell) \in W \). \( W \) is sound if:

1. \((W, [p_i]) \) is safe, i.e., \( \forall M \in R(W, [p_i]) (\forall p \in P (M(p) \leq 1)) \).
2. \([p_o]\) can always be reached, i.e., \( \forall M \in R(W, [p_i]) ((W, M) \sim (W, [p_o])) \).
3. Each \( t \in T \) is enabled, at some point, i.e., \( \forall t \in T (\exists M \in R(W, [p_i]) (M[t])) \).

Observe that, the Petri net depicted in Fig. 2 is a sound WF-net, i.e., it adheres to all three requirements of Definition 2.

2.3. Process Trees

Process trees allow us to model processes, that comprise a control-flow hierarchy. A process tree is a mathematical tree, where the internal vertices are operators and leaves are (non-observable) activities. Operators specify how their children, i.e., sub-trees, need to be combined from a control-flow perspective. Several operators can be defined, however, in this work, we focus on four basic operators, i.e., the \( \rightarrow, \times, \land \) and \( \lor \)-operator. The sequence operator \( (\rightarrow) \) specifies sequential behavior. First its left-most child is executed, then its second left-most child, ..., and finally its right-most child. For example, the root operator in Fig. 3 specifies that first activity \( a \) is executed, then its second sub-tree \( (\lor) \) and then its third sub-tree \( (\times) \). The exclusive choice operator \( (\times) \), specifies an exclusive choice, i.e., one (and exactly one) of its sub-trees is executed. Concurrent/parallel behavior is represented by the concurrency operator \( (\land) \), i.e., all children are executed simultaneously/in any order. Finally, we represent repeated behavior by the loop operator \( \lor \). Whereas the \( \rightarrow, \times \) and \( \land \)-operator have an arbitrary number of children, the \( \lor \)-operator has two children. Its left child (the “do-child”) is always executed. Secondly, executing its right child (the “re-do-child”) is optional. After executing the re-do-child, we again execute the do-child. We are allowed to repeat this, yet, we always finish with the do-child.

For example, consider Fig. 3, in which we depict an example process tree (describing the same language as the WF-net in Fig. 2). The root of the tree, i.e., \( v_{1.1} \), is a sequence operator, specifying that first its left-most child \( (v_{1.1}) \) needs to be executed. Its middle child, i.e., \( v_{1.2} \), represents a loop operator. The left sub-tree of the loop operator (i.e., having vertex \( v_{1.1} \) as its root) is always executed. Vertex \( v_{1.3} \) represents the “redo” part of the loop operator. The last part of the tree is represented by \( v_{1.2} \), i.e., specifying a choice construct between executing activity \( g \) or \( h \).

Definition 3 (Process Tree). Let \( \Sigma \) denote the universe of (activity) labels and let \( \tau \notin \Sigma \). Let \( \oplus \) denote the universe of process tree operators. A process tree \( Q \), is defined (recursively) as any of:

\[
\begin{align*}
\text{Note that various definitions of the loop operator exist, i.e., with three/an arbitrary number of children (e.g., [1, Definition 3.13]). However, all of these definitions can be rewritten into the binary loop operator, as described here.}
\end{align*}
\]
Interestingly, recursively inserting the $\hat{\lambda}$ depicted in Fig. 4. Note that, each transformation function in Fig. 4, is sound by construction.

Let $Q$ denote the universe of process trees. Given a process tree $Q \in Q$, its language is of the form $L_Q(Q) \subseteq \Sigma^*$, which is recursively defined in terms of of the languages of the children of a process tree. For example, the language of the $\rightarrow$ operator, is formed by concatenating any element of the language of its first child, with any element of its second child, etc. We formally define the language of a process tree as follows.

**Definition 4 (Process Tree Language).** Let $Q \in Q$ be a process tree. The language of $Q$, i.e., $L_Q(Q) \subseteq \Sigma^*$, is defined recursively as:

$$
L_Q(\tau) = \{ \epsilon \}, \text{ if } Q = \tau
$$

$$
L_Q(a) = \{ \langle a \rangle \} \text{ if } Q = a \in \Sigma
$$

$$
L_Q(Q) = \{ \sigma = \sigma_1 \cdot \sigma_2 \cdot \cdots \cdot \sigma_n \mid \sigma_1 \in L_Q(Q_1), \sigma_2 \in L_Q(Q_2), \ldots, \sigma_n \in L_Q(Q_n) \} \text{ if } Q = \rightarrow (Q_1, Q_2, \ldots, Q_n)
$$

$$
L_Q(Q) = \bigcup_{i=1}^{n} L_Q(Q_i) \text{ if } Q = \times (Q_1, Q_2, \ldots, Q_n)
$$

$$
L_Q(Q) = L_Q(Q_1) \cdot L_Q(Q_2) \cdot \cdots \cdot L_Q(Q_n) \text{ if } Q = \wedge (Q_1, Q_2, \ldots, Q_n)
$$

$$
L_Q(Q) = \{ \sigma_1 \cdot \sigma_1' \cdot \sigma_2 \cdot \sigma_2' \cdot \cdots \cdot \sigma_n \mid n \geq 1 \wedge 1 \leq i \leq n (\sigma_i \in L_Q(Q_i)) \wedge \forall 1 \leq i < n (\sigma_i' \in L_Q(Q_i')) \} \text{ if } Q = \circ (Q_1, Q_2)
$$

The process tree operators that we consider in this paper ($\rightarrow$, $\times$, $\wedge$ and $\circ$) are easily translated to sound WF-nets, cf. Fig. 4. Hence, we define a generic process tree to WF-net translation function, s.t., the language of the two is the same.

**Definition 5 (Process Tree Transformation Function).** Let $Q \in Q$ be a process tree. A process tree transformation function $\lambda$, is a function $\lambda : Q \rightarrow W$, s.t., $L_{\lambda}(\lambda(Q)) = L_Q(Q)$. We let

$\hat{\lambda} : Q \rightarrow N$, where, given $\lambda(Q) = W = (P, T, F, p_i, p_o, \ell)$, $\hat{\lambda}(Q) = (P', T, F', \ell')$, with, $P' = p \{ p_i, p_o \}$ and $F' = F \setminus \{ (p_i, t) \in F \} \cup \{ (t, p_o) \in F \}$.

Given an arbitrary process tree $Q \in Q$, there are several ways to translate it to a sound WF-net $W$, s.t., $L_{\lambda}(W) = L_Q(Q)$, i.e., instantiating $\lambda$ and $\hat{\lambda}$. As an example, consider the translation functions, depicted in Fig. 4. Note that, each transformation function in Fig. 4, is sound by construction. Interestingly, recursively inserting the $\hat{\lambda}$-generated fragments of the sub-trees of a given process.
When we find a pattern, we replace it with a smaller net fragment representing the process tree that was identified. We continue to search for patterns in the reduced net until we are not able to find any more patterns. As we prove in Section 3.4, in case the final WF-net contains just one transition, its label carries a process tree with the same labeled-language as the original WF-net.

Consider Fig. 5, in which we sketch the basic idea of the algorithm, applied on the example WF-net $W_1$ (Fig. 2). First, the algorithm detects two choice constructs, i.e., one between the transitions labeled $b$ and $c$, and one between the transitions labeled $g$ and $h$. The algorithm replaces the fragments by means of two new transitions, carrying labels $\times(b,c)$ and $\times(g,h)$ respectively (Fig. 5a). Subsequently, a concurrent construct is detected, i.e., between the transitions labeled $\times(b,c)$ and $d$. Again, the pattern is replaced (Fig. 5b). A sequential pattern is detected and replaced (Fig. 5c), after which a loop construct is detected (Fig. 5d). The resulting process tree, i.e., carried by the remaining transition in Fig. 5e, $\rightarrow((a \cup (\rightarrow(\&\times(b,c),d),c),f),\times(g,h))$, is equal to Fig. 3.

### 3.2. PTree-Nets and their Unfolding

As indicated, we aim to find Petri net fragments in the WF-net representing behavior equivalent to a process tree. As illustrated in Section 3.1, the patterns found in the WF-net are replaced by transitions with a label carrying a corresponding process tree. In the upcoming section, we present four different fragment characterizations, corresponding to the basic process tree operators considered. However, in this section, we first briefly present PTree-nets, i.e., a trivial extension of Petri nets, in which labels are process trees.

**Definition 6** (Process Tree-labeled Petri-net (PTree-net)). Let $Q$ denote the universe of process trees. Let $P$ denote a set of places, let $T$ denote a set of transitions, let $F \subseteq (P \times T) \cup (T \times P)$ denote the arc relation and let $\kappa: T \rightarrow Q$. Tuple $N = (P, T, F, \kappa)$ is a Process Tree-labeled Petri net (PTree-net). $N_Q$ denotes the universe of PTree-nets.

Given $N \in N_Q$, for any marking $M, M'$ we have $\kappa(L_N(x, N, M, M')) \in Q^*$, and, $L_Q(\kappa(\kappa(L_N(x, N, M, M')))) \in \Sigma^*$, i.e., the definition of $L_Q$ ignores $\tau \notin \Sigma$. Clearly, since PTree-nets extend the labelling function to $Q$, PTree-System-nets, and, PTree-WF-nets are readily defined. We let $SN_Q$ and $W_Q$ represent their respective universes. Note that, we use a different symbol to indicate whether a labeling function maps to $Q$ or $\Sigma \cup \{\tau\}$, i.e., $\kappa: T \rightarrow Q$, whereas $\ell: T \rightarrow \Sigma \cup \{\tau\}$.

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2 Note that, certain proofs presented later build upon the recursive nature of the translations ad presented in Fig. 4.

3 Observe: $L_N(x, N, M, M') = \kappa(L_N(x, N, M, M'))_{\kappa} = L_Q(\kappa(L_N(x, N, M, M')))$. 


Since functions are binary Cartesian products, we write set operations here.

**Definition 7 (PTree-net Unfolding).** A PTree-net unfolding \( \Lambda : \mathcal{N}_Q \rightarrow \mathcal{N} \) is a function where, given \( N=(P,T,F,\kappa) \in \mathcal{N}_Q \), \( \Lambda(N)=(P',T',F',\ell) \), with:

1. \( P' = P \cup \bigcup_{t \in T} \hat{P}_t \)
2. \( T' = \bigcup_{t \in T} \hat{T}_t \)
3. \( F' = \bigcup_{t \in T} \hat{F}_t \cup \{ (p,t) \mid p \in \bullet \land t \in p_1 \} \cup \bigcup_{t \in T} \{ (t,p) \mid p \in \bullet \land t \in p_0 \} \)
4. \( \ell = \bigcup_{t \in T} \hat{\ell}_t \). \(^4\)

Observe that, under the assumption that we use the instantiation of \( \lambda \) as shown in Fig. 4, indeed, each transition in the unfolding of a PTree-net has a corresponding label in \( \Sigma \cup \{ \tau \} \). Furthermore, note that, unfolding the WF-net in Fig. 5a yields the original model in Fig. 2. The unfolding of the other WF-nets in Fig. 5 yields a different WF-net. However, the language of all unfolded WF-nets remains equal to the language of the WF-net in Fig. 2.

\(^4\) Since functions are binary Cartesian products, we write set operations here.
3.3. Pattern Reduction

In this section, we describe four patterns used to identify and replace process tree behavior. Furthermore, we propose a corresponding overarching reduction function, which shows how to reduce a PTree-WF-net containing any of these patterns. However, first, we present the general notion of a feasible pattern. Such a feasible pattern is a system net, formed by a place-bordered fragment of a given PTree-net. Furthermore, the language of the unfolding of the system net needs to be equal to the language of the process tree it represents. We formalize the notion of a feasible pattern as follows.

Definition 8 (Feasible Pattern). Let \( \oplus \) denote the universe of process tree operators. Let \( N=(P,T,F,\kappa)\in\mathcal{N}_Q \), let \( N'=(P',T'={\{t_1, \ldots, t_n\}, F',\kappa|_{T'}})\subseteq N \) be a place-bordered fragment of \( N \) with corresponding input places \( P'_i \) and output places \( P'_o \). Let \( M_i=P_i \) and \( M_f=P_o \). Given \( \oplus \in \Theta_P, SN=(N', M_i, M_f) \in SN_Q \) is a feasible \( \oplus \)-pattern, written \( \theta_\oplus(N, SN) \), iff:

\[
\mathcal{L}_Q \left( \oplus \left( \kappa(t_1), \ldots, \kappa(t_n) \right) \right) = \mathcal{L}_Q^N \left( \Lambda \left( N' \right), M_i, M_f \right)
\]

Observe that any place-bordered fragment of a WF-net that describes the same local language as its corresponding process tree representation is a feasible pattern. As such, any feasible pattern is locally language-preserving. Transforming such a detected pattern within the given WF-net is straightforward, i.e., we add a new transition \( t' \) to the WF-net with label \( \oplus \left( \kappa(t_1), \ldots, \kappa(t_n) \right) \) and pre-set \( P_i \) and post-set \( P_o \). For example, consider the reduction of the choice construct between transitions \( t_2 \) and \( t_3 \) of Fig. 2, i.e., depicted in Fig. 5a, in which places \( p_1 \) and \( p_3 \) serve as the pre and post set of the newly added transition \( t'_2 \) with label \( \times(b, c) \). We formally define the notion of feasible pattern reduction as follows.

Definition 9 (Pattern Reduction). Let \( \oplus \in \{\to, \times, \land, \lor, \to\} \), let \( N=(P,T,F,\kappa)\in\mathcal{N}_Q \), let \( N'=(P',T'={\{t_1, \ldots, t_n\}, F',\kappa|_{T'}})\subseteq N \) be a place-bordered fragment of \( N \) with corresponding input places \( P_i \) and output places \( P_o \). Let \( M_i=P_i \), \( M_f=P_o \) and let \( SN=(N', M_i, M_f) \) s.t. \( \theta_\oplus(N, SN) \). We let \( \Theta_\oplus(N, SN)=N''=(P'', T'', F'', \kappa') \) denote the \( \Theta_\oplus(N, SN) \)-reduced PTree-net, with, for \( t' \not\in T' \):

\[
\begin{align*}
P'' &= (P\setminus P') \cup P_i \cup P_o \\
T'' &= (T\setminus T') \cup \{t'\} \\
F'' &= (F\setminus F') \cup \{(p, t')|p \in P\} \cup \{(t', p)|p \in P_o\} \\
\kappa' &= \kappa|_{T''} \cup \{(t', \oplus(\kappa(t_1), \ldots, \kappa(t_n))\}\}
\end{align*}
\]

A feasible pattern \( \theta_\oplus(N, SN) \) is globally language preserving iff

\[
\forall M, M' \in \mathcal{M}(P'') \left( \mathcal{L}_\kappa^N(\Lambda(N), M, M') = \mathcal{L}_\kappa^N(\Lambda(N''), M, M') \right)
\]

It is important to note that the notion of globally language-preserving is defined on the unfolding of a net and its corresponding reduced net. For example, consider Fig. 6. In the WF-net in Fig. 6a, we observe concurrent behavior between a sequential construct between \( a \) and \( c \), and, activity \( b \). The fragment formed by \( p_1, p_3, p_5 \) and \( t_2 \) and \( t_4 \), is a feasible sequence pattern. In Fig. 6b, we depict the reduced counterpart of the net in Fig. 6a, in which transitions \( t_2 \) and \( t_4 \), and the place connecting them, i.e., \( p_5 \), are replaced by transition \( t'_2 \) with label \( \to(a, c) \). Observe that, the language of the original net (Fig. 6a) is \( \{\langle t_1, t_2, t_3, t_4, t_5\rangle, \langle t_1, t_3, t_2, t_4, t_5\rangle, \langle t_1, t_2, t_4, t_3, t_5\rangle\} \), whereas the language of the corresponding reduced net (Fig. 6b) is \( \{\langle t_1, t_2, t_2, t_2, t_2, t_2\rangle, \langle t_1, t_5, t_2, t_2, t_2\rangle\} \). Consequently, the corresponding labeled languages are \( \{\langle a, b, c\rangle, \langle b, a, c\rangle, \langle a, c, b\rangle\} \) and \( \{\langle \to(a, c), b\rangle, \langle b, \to(a, c)\rangle\} \) respectively. The labeled language of the reduced net, after evaluating the process tree fragments inside, yields \( \{\langle a, c, b\rangle, \langle b, a, c\rangle\} \), i.e., the trace \( \langle a, b, c\rangle \) is not in the corresponding language. However, if we first unfold the label of \( t'_2 \) in Fig. 6b, i.e., yielding the model in Fig. 6a (modulo renaming of transitions), the labeled languages of the two nets are indeed equal, i.e., they both describe \( \{\langle a, b, c\rangle, \langle b, a, c\rangle, \langle a, c, b\rangle\} \).
(a) A WF-net describing concurrent behavior between a sequential construct between $a$ and $c$, and, activity $b$. Observe that, the fragment formed by $p_1, p_3, p_5$ and $t_2$ and $t_4$ is a feasible sequence pattern.

(b) The (PTree)WF-net after reduction of the sequential pattern between $t_2$ and $t_4$.

Figure 6. Example WF-net (and a corresponding reduction) in which we are able to detect the feasible pattern $\to(a, c)$. The language of the original net (Fig. 6a) is $\{\langle t_1, t_2, t_3, t_4, t_5 \rangle, \langle t_1, t_3, t_4, t_5 \rangle, \langle t_1, t_2, t_3, t_5 \rangle\}$. The language of the reduced net (Fig. 6b) is $\{\langle t_1, t'_2, t_3, t_5 \rangle, \langle t_1, t_3, t'_2, t_5 \rangle\}$. Applying the label functions on the firing sequences yields different labeled languages.

Furthermore, observe that there exist feasible patterns that are locally language-preserving, yet, not globally language-preserving. For example, consider the WF-net in Fig. 7. The place-bordered fragment formed by the subnet consisting of places $p_1$ and $p_2$ and transitions $t_2$ and $t_3$ (with the arcs connecting them), form a feasible pattern corresponding to $\cup (a, b)$ (with $M_i = [p_1]$ and $M_f = [p_2]$).

However, note that after reduction, i.e., by inserting $t'_2$, we obtain a WF-net that no longer has the same language as the original model. This is because, before reduction, executing transition $t_5$ allows us to enable transition $t_3$. After reduction, however, this is no longer possible. Hence, whereas the observed feasible pattern is locally language preserving, i.e., when considering the elements it is composed of, it is not globally language-preserving.

In the upcoming paragraphs, we characterize an instantiation of a global language preserving feasible pattern for each process tree operator considered in this paper. For each proposed pattern, we prove that it is both locally and globally language preserving.

3.3.1. Sequential Pattern

The $\to$-operator, i.e., $\to (Q_1, ..., Q_n)$, describes sequential behavior, hence, any subnet describing strictly sequential behavior, describes the same language. If a transition $t_1$ always, uniquely, enables transition $t_2$, which in turn enables transition $t_3, ..., t_n$, and, whenever $t_1$ has fired, the only way to consume all tokens from $t_1$, is by means of firing $t_2$, and similarly, the only way to consume all tokens from $t_2$, is by means of firing $t_3$, etc., then $t_1, ..., t_n$ are in a sequential relation. We visualize the $\to$-pattern in the left-hand side of Fig. 8.\(^5\)

We formally define the notion of a sequential pattern as follows

\(^5\) In the visualization, we omit $P_i$ and $P_o$ respectively, i.e., $\bullet t_1$ and $t_n \bullet$. 
Proposition 1 (→-Pattern). Let $N=(P,T,F,\kappa)\in\mathcal{N}_Q$ and let $T' = \{t_1, \ldots, t_n\} \subseteq T$ ($n \geq 2$). If and only if:

1. $\forall 1 \leq i < n (|t_i\bullet| \geq 1 \land \exists_1 \bullet = t_{i+1})$; transition $t_i$ enables $t_{i+1}$,
2. $\forall 1 \leq i < n (\forall p \in t_i\bullet (\exists p = \{t_i\} \lor \bullet = \{t_{i+1}\}))$; enabling is unique,

then, system net $SN= (N'=(P',T',F',\kappa|_{T'}), \bullet t_1, t_n$) ($P'=\bullet t_1 \cup \bullet t_2 \cup \cdots \cup \bullet t_n \cup t_n\bullet$, $F' = \{(x,y)\in F \mid y\in T'|x=t_n\}$), is a feasible →-pattern.

Proof. Observe that $t_1$ is the only enabled transition in marking $M_1=P_1$. By definition of the proposed pattern, after firing $t_i$ ($1 \leq i < n$), the only enabled transition is $t_{i+1}$. After firing $t_n$ we reach the final marking $M_f$, which is a deadlock marking (the only deadlock marking) of the place-bordered subnet. Hence, any firing sequence of $\Lambda(N')$ can be written as $\sigma_1 \circ \sigma_2 \cdots \circ \sigma_n$, s.t.,

$(\Lambda(N'), M_f) \xrightarrow{\sigma_1} (\Lambda(N'), t_1\bullet) \xrightarrow{\sigma_2} \cdots \xrightarrow{\sigma_n} (\Lambda(N'), M_f)$. Observe that each element of $\sigma_1$ is a transition in $\lambda(\kappa(t_1))$, each element of $\sigma_2$ is a transition in $\lambda(\kappa(t_2))$, etc. Furthermore, by definition of $\lambda$, $\sigma_1$ is a firing sequence describing (when projected on its visible labels) a member of $\mathcal{L}_Q(\kappa(t_1))$, $\sigma_2$ describes as sequence in $\mathcal{L}_Q(\kappa(t_1))$, etc. Hence, the set of all firing sequences projected on their visible labels equals $\mathcal{L}_Q(\rightarrow(\kappa(t_1), \kappa(t_2), \ldots, \kappa(t_n)))$. \hfill $\square$

Lemma 1 (→-Pattern (Proposition 1) is Globally Language-Preserving). Let $N=(P,T,F,\kappa)\in\mathcal{N}_Q$ and let $SN=(N'=(P',T'=\{t_1, t_2, \ldots, t_n\}, F', \kappa|_{T'}), \bullet t_1, t_n\bullet$ s.t. $\theta_{\rightarrow}(N,SN)$ according to Proposition 1. The feasible pattern $\theta_{\rightarrow}(N,SN)$ is globally language-preserving.
Proof. Let \( N'' \) denote the net obtained after reduction (cf. Definition 9) and let \( P''=(P\setminus P')\cup P_1\cup P_o \). We need to prove that \( \forall M, M'\in M(P'') \) \( \mathcal{L}_{\lambda'}(\Lambda(N), M, M')=\mathcal{L}_{\lambda'}(\Lambda(N''), M, M') \).

Observe that \( \Lambda(N) \) and \( \Lambda(N'') \) are identical, except for \( \Lambda(N') \) in \( N \) and \( \hat{\lambda}(t') \) (the transition-bordered unfolding of the newly added transition \( t' \)) in \( N'' \) respectively. The only connections between \( N' \) in \( N \) and \( t' \) in \( N'' \) with the identical parts of the two nets are through \( P_1 \) and \( P_o \).

Hence, if there exists a visible firing sequence in \( \mathcal{L}_{\lambda'}(\Lambda(N), M, M') \) that is not in \( \mathcal{L}_{\lambda'}(\Lambda(N''), M, M') \), this can only be due to different behavior described by \( \Lambda(N') \) and \( \hat{\lambda}(t') \). However, this directly contradicts feasibility of the pattern. 

3.3.2. Exclusive Choice Pattern

The \( \times \)-operator, i.e., \( \times (Q_1, ..., Q_n) \), describes “execute either one of \( Q_1, ..., Q_n \)”.

Proposition 2 (\( \times \)-Pattern). Let \( N=(P,T,F,\kappa)\in\mathcal{N}_Q \) and let \( T'=\{ t_1, ..., t_n \} \subseteq T \) (\( n \geq 2 \)). If and only if:

1. \( \bullet t_1=\bullet t_2=\cdots=\bullet t_n; \) all pre-sets are shared among the members of the pattern,
2. \( t_1\bullet= t_2\bullet=\cdots= t_n\bullet; \) all post-sets are shared among the members of the pattern,
3. \( \forall 1 \leq i \leq n \text{ (} t_i \neq t_1\bullet \); self-loops are not allowed.

then, system net \( SN=(N'=\langle P',T',F',\kappa|_{T'} \rangle, \bullet t_1, t_1\bullet) \) \( (P'=t_1\cup t_1\bullet, \) with \( P'=t_1\cup t_1\bullet, \)

\( F'=\{(x,y)\in F \mid x\in T'\lor y\in T'\} \), is a feasible \( \times \)-pattern.

Proof. Observe that \( t_1, t_2, ..., t_n \) are the only enabled transitions in \( N' \) in marking \( M_i=P_i \). When we fire any one of these transitions, we immediately mark \( P_o \), which is the final marking of the system net.

Hence, the set of firing sequences of the system net is the union of the set of sequences \( \langle \Lambda(N'), M_i \rangle \mapsto \langle \Lambda(N'), M_i \rangle \) where \( \sigma \) either corresponds to a labelled language of \( \mathcal{L}_Q(\kappa(t_1)) \), or \( \mathcal{L}_Q(\kappa(t_2)) \), ..., or \( \mathcal{L}_Q(\kappa(t_n)) \). Observe that, indeed, this set corresponds to \( \mathcal{L}_Q(\times(\kappa(t_1), \kappa(t_2), ..., \kappa(t_n))) \).

Lemma 2 (\( \times \)-Pattern (Proposition 2) is Globally Language-Preserving). Let \( N=(P,T,F,\kappa)\in\mathcal{N}_Q \) and let \( SN=(N'=\langle P',T'=\{ t_1, t_2, ..., t_n \}, F',\kappa|_{T'} \rangle, \bullet t_1, t_1\bullet) \) s.t. \( \theta_x(N,SN) \) according to Proposition 2. The feasible pattern \( \theta_x(N,SN) \) is globally language-preserving.

Proof. Let \( N'' \) denote the net obtained after reduction (cf. Definition 9) and let \( P''=(P\setminus P')\cup P_1\cup P_o \).

Observe that, similar to the sequential pattern, \( \Lambda(N) \) and \( \Lambda(N'') \) are identical, except for \( \Lambda(N') \) and \( \hat{\lambda}(t') \) respectively. Again, the only connections between \( N' \) and \( t' \) with the identical parts of the two nets are through \( P_1 \) (“entering”) and \( P_o \) (“exiting”). Hence, if there exists a visible firing sequence in \( \mathcal{L}_{\lambda'}(\Lambda(N), M, M') \) that is not in \( \mathcal{L}_{\lambda'}(\Lambda(N''), M, M') \), this can only be due to different behavior described by \( \Lambda(N') \) and \( \hat{\lambda}(t') \), again contradicting the feasibility of the pattern.
3.3.3. Concurrent Pattern

The concurrent pattern is the most complicated pattern that we consider in this paper. In the concurrent pattern, interference between its transitions is possible. The interference is achieved by requiring that the pre-sets and post-sets of the transitions do not have any overlap. Furthermore, the pre-set of the transition’s pre-set places needs to be shared by all of these places, and, symmetrically, the post-set of the transition’s post-set places needs to be shared by all of these places. That is, the enabling of the transitions in the pattern needs to be the same, and their post-set should jointly block any further action (i.e., within its local scope) until all places in their joint post-set are marked. Consider the left-hand side of Fig. 10, in which we schematically depict the concurrent pattern, which we formalize in Proposition 3.

**Proposition 3 (∧-Pattern).** Let \( N = (P, T, F, \kappa) \in N_Q \) and let \( T' = \{ t_1, ..., t_n \} \subseteq T (n \geq 2) \). If and only if:

1. \( \forall 1 \leq i < j \leq n \ (\bullet t_i \cap \bullet t_j = \emptyset) \); no interaction between the member’s pre-sets,
2. \( \forall 1 \leq i < j \leq n \ (\bullet t_i \cap \bullet t_j = \emptyset) \); no interaction between the member’s post-sets,
3. \( \forall 1 \leq i \leq n \ (\forall p \in \bullet t_i \ (p = \{ t_i \})) \); pre-set places uniquely connect to a member,
4. \( \forall 1 \leq i \leq n \ (\forall p \in \bullet t_i \ (p = \{ t_i \})) \); post-set places uniquely connect to a member,
5. \( \forall p \in T \ (p \cap \{ t_1, ..., t_n \} = \emptyset) \); members do not influence other members,
6. \( \forall p, p' \in T \ (p = p') \); member’s pre-sets share their pre-set,
7. \( \forall p \in T \ (p \cap \{ t_1, ..., t_n \} = \emptyset) \); member firing does not affect other members,
8. \( \forall p, p' \in T \ (p = p') \); member’s post-sets share their post-set,
9. \( \forall t, t' \in (T) \ (t = t') \); pre-sets of enablers are equal,
10. \( \forall t, t' \in (T) \ (t = t') \); post-sets of enablers are equal,

then, system net \( \text{SN} = (N' = (P', T', F', \kappa|_{T'}), \bullet T', T'^*) \ (P_i = T', \ P_o = T'), \) with \( P' = T \cup \bullet \), \( F' = \{ (x, y) \in F \mid (x \in P' \wedge y \in T') \vee (x \in T' \wedge y \in P') \} \) is a feasible ∧-pattern.

**Proof.** Observe that, \( t_1, t_2, ..., t_n \) are the only enabled transitions in \( N' \) in marking \( M_i = P_t \). Furthermore, since none of the transitions share any of their presets, the transitions can be fired in any order. Note that, by definition of the pattern, after all transitions have fired, we reach final marking \( M_f \) (which is a deadlock in the place-bordered system net). Hence, the labeled language described by the pattern equals \( \mathcal{L}_Q(\kappa(t_1)) \equiv \mathcal{L}_Q(\kappa(t_2)) \equiv \cdots \equiv \mathcal{L}_Q(\kappa(t_n)) \), which equals \( \Lambda(\kappa(t_1), \kappa(t_2), ..., \kappa(t_n)) \).

**Lemma 3 (∧-Pattern (Proposition 3) is Globally Language-Preserving).** Let \( N = (P, T, F, \kappa) \in N_Q \) and let \( \text{SN} = (N' = (P', T', F', \kappa|_{T'}), \bullet T', T'^*) \) \( s.t. \theta_N(N, \text{SN}) \) according to Proposition 3. The feasible pattern \( \theta_N(N, \text{SN}) \) is globally language-preserving.

**Proof.** Observe that, \( \Lambda(N) \) and \( \Lambda(N') \) are identical, except for \( \Lambda(N_i) \) and \( \Lambda(t'_i) \) respectively. Again, the only connections between \( N' \) and \( t'_i \) with the identical parts of the two nets are through \( P_i \) (“entering”) and \( P_o \) (“exiting”). Hence, if there exists a visible firing sequence in \( \mathcal{L}_X(\Lambda(N), M, M') \) that is not in \( \mathcal{L}_X(\Lambda(N'), M, M') \), this can only be due to different behavior described by \( \Lambda(N) \) and \( \Lambda(t'_i) \), again contradicting the feasibility of the pattern.
3.3.4. Loop Pattern

The final operator we consider is the $\bowtie$-operator, i.e., the only operator with just two children. Hence, the fragments representing a loop pattern in the Ptree-net consist of two transitions. Consider the left-hand side of Fig. 11, in which we schematically depict the loop pattern fragment. Conceptually, the loop operator requires us first to execute its leftmost child (the “do-part”). Secondly, its rightmost child is optionally executed (the “redo-part”). However, we always finish with the leftmost child. As such, the post-set of a transition corresponding to the do-part needs to be the pre-set of the transition that represents the redo-part. Furthermore, there should be no other way to enable the redo-part. Hence, the do-part needs to be the only transition that marks the pre-set of the redo-part. Similarly, to guarantee global language preservation, the do-part should be the only element in the post-set of its pre-set, i.e., no other transition may be enabled by the pre-set of the do-part. Reconsider Fig. 7, observe that $p_2$ contains multiple incoming and outgoing arcs, hence, it does not describe a loop-pattern for transitions $t_2$ and $t_3$, nor for transitions $t_4$ and $t_5$.

**Proposition 4** ($\bowtie$-Pattern). Let $N=(P,T,F,\kappa)\in\mathcal{N}_Q$ and let $t_1 \neq t_2 \in T$. Iff:

1. $t_1 \cdot = t_2 \cdot$: pre-set of $t_1$ is the post-set of $t_2$,
2. $t_1 \cdot = t_2 \cdot$: pre-set of $t_2$ is the post-set of $t_1$,
3. $\forall p \in t_1 \{ p = \{ t_1 \} \}; t_1$ is the only transition in the post-set of its pre-set,
4. $\forall p \in t_1 \{ p = \{ t_1 \} \}; t_1$ is the only transition in the pre-set of its post-set

Then, system net $SN = \{ N' = (P', T', F', \kappa_{\{t_1,t_2\}}), t_1 \cdot, t_1 \cdot \} (P_1 = t_1 \cdot, P_2 = t_2 \cdot)$, with $P' = t_1 \cup t_1 \cdot,$

$T' = \{ t_1, t_2 \}, F' = \{ (x,y) \in F \mid x \in \{ t_1, t_2 \} \forall y \in \{ t_1, t_2 \} \}$ is a feasible $\bowtie$-pattern.

**Proof.** Observe that $t_1$ is the only enabled transition in $N'$ in marking $M_1 = P_1$. When we fire it, we immediately mark $P_0$, which is the final marking of the borderless-systemed net. In said marking, $t_2$ is the only enabled transition. Firing $t_2$ yields us with marking $M_1$. Again. We can repeat this infinitely. Hence, the labeled language described by the pattern is $\{ \sigma_1 \sigma_1' \sigma_2 \sigma_2' \cdots \sigma_n \mid n \geq 1 \land \forall 1 \leq i \leq n (\sigma_i \in \mathcal{L}_Q(\kappa(t_1))) \land \forall 1 \leq i < n (\sigma_i' \in \mathcal{L}_Q(\kappa(t_2))) \}$, which equals $\bowtie (\mathcal{L}_Q(\kappa(t_1)), \mathcal{L}_Q(\kappa(t_2)))$.

**Lemma 4** ($\bowtie$-Pattern (Proposition 4) is Globally Language-Preserving). Let $N=(P,T,F,\kappa)\in\mathcal{N}_Q$ and let $SN=(N'=(P', T'=\{t_1,t_2,\ldots,t_n\}, F',\kappa|_{T'}), t_1 \cdot, t_1 \cdot)$ s.t. $\theta_{\bowtie}(N,SN)$ according to Proposition 4. The feasible pattern $\theta_{\bowtie}(N,SN)$ is globally language-preserving.

**Proof.** Let $N''$ denote the net obtained after reduction (cf. Definition 9) and let $P''=(P \setminus P') \cup P \cup P_0$. Observe that, $\Lambda(N)$ and $\Lambda(N'')$ are identical, except for $\Lambda(N')$ and $\lambda'(t')$ respectively. Again, the only connections between $N'$ and $t'$ with the identical parts of the two nets are through $P_1$ (“entering”) and $P_0$ (“exiting”). In particular, when $P_1$ is marked, the only way to mark $P_0$ is by firing $t_1$, followed by an arbitrary number of $(t_2,t_1)$ repetitions. Hence, if there exists a visible firing sequence in $\mathcal{L}_Q(\Lambda(N), M, M')$ that is not in $\mathcal{L}_Q(\Lambda(N''), M, M')$, this can only be due to different behavior described by $\Lambda(N')$ and $\lambda'(t')$, contradicting the feasibility of the pattern.
4. Algorithm

In this section, we present an algorithm that iteratively applies the reductions defined in Section 3.3. By doing so, the algorithm is able to translate a WF-net into a process tree. We prove that, if the algorithm terminates correctly, i.e., it finds a process tree, the input WF-net is sound. Moreover, we show that the language of the input WF-net equals the language of the process tree found.

Consider Algorithm 1, in which we present an algorithmic description of the reduction algorithm, on the basis of the proposed patterns in Section 3.3. As an input, the algorithm needs any WF-net \( W \), which, by definition, is also a PTWF-net. Initially, the elements of \( p_{\text{incoming}} \) and place \( p_{\text{place}} \) are copied into variables \( P \) and \( F \). In case any pattern of the form \( \theta_{\oplus}(N, SN) \) is found in \( N \), the corresponding reduction \( \Theta_{\oplus}(N, SN) \) is applied (line 3). If no more pattern is found, the algorithm returns \( (N, p_i, p_o, \kappa) \). The algorithm returns the most recent reduction, if no more pattern is found. Observe that, intentionally, the order and size of the patterns to be reduced is not specified, i.e., it is of no relevance to any of the lemmas and the theorems regarding the algorithms properties and correctness.

In case the obtained PTree-WF-net consists of just one transition, i.e., connected to place \( p_i \) (incoming) and place \( p_o \) (outgoing), cf. Fig. 5e, the label of the transition represents a process tree, describing the same language as the original WF-net. Furthermore, we can conclude that the original WF-net is, in fact, a sound WF-net. We prove these observations in Theorem 1. However, before this, we first present two useful lemmas. In Lemma 5, we prove that the proposed reduction rules are bidirectionally soundness preserving, i.e., if a PTree-WF-net is sound, the reduced PTree-WF-net is sound (and vice versa). In Lemma 6, we prove that, if we are able, from the initial marking \([p_i]\), to enable the observed fragment (enabling differs per fragment), then the language of the original net and the reduced net is equal (and vice versa). Observe that, trivially, the reduction rules applied on a PTree-WF-net yield a PTree-WF-net, i.e., none of the requirements of Definition 1 are violated on the resulting net.

Lemma 5 (Pattern Reduction is Soundness Preserving). Let \( \oplus \in \{\rightarrow, \times, \land, \lor\} \), let \( W = (P, T, F, p_i, p_o, \kappa) \in \mathcal{W} \), let \( SN \in \mathcal{SN} \), s.t., \( \theta_{\oplus}(W, SN) \), and, let \( W^\prime = (P', T', F', p_i, p_o, \kappa') = \Theta_{\oplus}(W, SN) \in \mathcal{W} \). \( W' \) is sound iff \( W \) is sound.

Proof. \((\Rightarrow)\) Let \( t^' \in T \setminus T' \). Assume that \( W \) is sound, yet, \( W' \) is not sound. By definition of any reduction \( \Theta_{\oplus}(W, SN) \), if \( W' \) is not safe, then \( W \) is not safe. For any \( t \in T \cap T' \), if \( \exists M \in \mathcal{R}(W', [p_i]) ((W', M)[t]) \), then also, \( \exists M \in \mathcal{R}(W, [p_i]) ((W, M)[t]) \). Similarly, if \( \exists M \in \mathcal{R}(W', [p_i]) ((W', M)[t']) \), then this also holds for the transitions in \( SN \). In case \( \exists M \in \mathcal{R}(W', [p_i]) \) s.t. \( \exists \sigma \in T^* \ (W', M) \overset{\sigma}{\rightarrow} (W', [p_o]) \), then, again by definition of the reductions, also \( M \in \mathcal{R}(W', [p_i]) \) and \( \exists \sigma \in T^* \ (W, M) \overset{\sigma}{\rightarrow} (W, [p_o]) \), contradicting soundness of \( W \).

\((\Leftarrow)\) Assume that \( W' \) is sound, yet, \( W \) is not sound. Given that \( W' \) and \( W \) only differ on \( t' \) and \( SN \) respectively, the “non-sound” part of \( W \) needs to be part of \( SN \). However, it is easy to see that none of the patterns defined in Section 3.3 do not specify any non-sound construct. Hence, replacing \( SN \), implies that \( W' \) needs to be unsound, which contradicts the assumption. \( \square \)
Lemma 6 (Pattern Reduction is Language Preserving in $\Lambda$). Let $\oplus \in \{\rightarrow, \times, \wedge, \lor\}$, let $W = (P, T, F, p_i, p_o, \kappa) \in W_Q$, let $SN \in SN_Q$, s.t., $\theta_{\oplus}(W, SN)$, and let $W' = (P', T', F', p'_i, p'_o, \kappa') \in W_Q$ be the resulting WF-net of Algorithm 1 on $W$. If $P' = \{p_i, p_o\}$, $T' \{t\}$, and $F = \{(p_i, t), (t, p_o)\}$, then, $L_{\Lambda}(\kappa(t)) = L_{\Lambda}(W)$.

Proof. Trivially follows from Lemmas 1-4.

Theorem 1 (Algorithm 1 is able to find Language-Equal Process Trees). Let $W = (P, T, F, p_i, p_o, \ell) \in W$ and let $W' = (P', T', F', p'_i, p'_o, \kappa') \in W_Q$ be the resulting WF-net of Algorithm 1 on $W$. If $P' = \{p_i, p_o\}$, $T' \{t\}$, and $F = \{(p_i, t), (t, p_o)\}$, then, $L_{\Lambda}(\kappa(t)) = L_{\Lambda}(W)$.

Proof. Observe that, $W$ is sound. Lemma 5 implies that if we (continuously) revert the reductions applied by Algorithm 1, i.e., corresponding to all intermediate assignments of $W$ in Algorithm 1, all reverted nets are sound. Observe that, Lemma 6 proves that the language of the unfoldings of all the intermediate WF-nets found is the same as well. Since the labels of the initial WF-net are all members of $\Sigma \cup \{\tau\}$, their unfolding remains the same. Hence, we deduce $L_{\Lambda}(\kappa(t)) = L_{\Lambda}(W)$.

It is important to note that the algorithm nor the supporting lemmas and proofs specify any condition on order and the size of the pattern(s) to be reduced. In fact, the size of the pattern reduced is not of influence w.r.t. any of the correctness proofs. Note that, indeed, the correctness of the proposed algorithm.

4. Evaluation

In this section, we evaluate the proposed algorithm. We briefly present the implementation, after which we discuss the experimental setup and the results.

4.1. Implementation

An implementation of Algorithm 1 is available\(^7\), i.e., built on top of the process mining framework PM4Py\(^10\). As indicated, the size of the patterns identified has no influence on the correctness of the algorithm. Hence, the implementation searches for binary patterns, yielding binary trees. Such a tree can be further reduced, e.g., $\rightarrow (Q_1 \rightarrow (Q_2, \rightarrow (Q_3, \tau)))$ corresponds to $\rightarrow (Q_1, Q_2, Q_3)$.

4.2. Experimental Setup

Here, we briefly discuss the experimental setup of our experiments. Consider Fig. 12, in which we present a graphical overview. Using an implementation of PTandLogGenerator\([14,15]\), we generate process trees, using two triangular distributions for the number of activities, i.e., $\{10, 20, 30\}$ and $\{40, 50, 60\}$. The process trees are translated to WF-nets, using two different translations. One translation creates invisible start and end transitions for each operator; the other translation only does so when required (similar to Fig. 4). The first translation generates larger nets in terms of transitions/places/arc.

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\(^6\) As a corollary of this fact, it follows that $W$ is sound.

\(^7\) https://github.com/s-j-v-zelst/pm4py-source/blob/pn_to_pt/scripts/pn_to_pt.py
Figure 13. Average time performance of the implementation. A quadratic relation, in computation time measured in micro-seconds ($\mu$-seconds), w.r.t. the size of the WF-net, is observable.

process trees (yielding 200,000 experiments). Finally, we compare the generated process tree in canonical form [16, Section 5.1], to the resulting process tree in canonical form.

4.3. Results

Here, we briefly discuss the results of the conducted experiments. Consider Fig. 13, in which we present the average time performance of the implementation on the data as generated according to the described experimental setup. We plot the time performance, conditional to the size of the input WF-net. Additionally, we plot a polynomial trend-line, computed using polynomial least squares. As is clearly observable in Fig. 13, the time performance is quadratic in the size of the net ($|P| + |T|$). This is confirmed by the $R^2$-score of the trend-line, i.e., $\sim 0.988$. In all experiments, the canonical form of the generated process tree equals the canonical form of the (re)discovered process tree.

5. Related Work

Process trees are often used in the domain of process mining. However, a complete overview of the field is outside of scope, i.e., we refer to [1] for a gentle introduction. Similarly, we refer to [17] for an in-depth overview of process discovery algorithms, and, we refer to [18] for an overview of the sub-field of conformance checking.

The conceptual idea of transforming a given process model in a certain formalism $F$ into an alternative process modeling formalism $F'$ is well-studied. Transformations of graph-oriented modeling formalisms, e.g., Petri nets, and block-oriented modeling formalisms, e.g., Process Trees, are often studied. In [19], the authors generalize work that transforms (both ways) graph-based process modeling formalisms into Business Process Execution Language for Web services (BPEL) (an XML-based format). The authors characterize several strategies for such translations. In this context, the work presented in this paper belongs to the structure-identification category.

Of particular interest is the work of van der Aalst and Lassen [20,21], i.e., on translating of WF-nets to BPEL. In the work, XML fragments of BPEL are generated on the basis of a given WF-net. Since XML, by definition, is a tree-like data representation, BPEL and process trees are conceptually close. The algorithm replaces components, i.e., connected, complete subnets with a unique start and end element, i.e., such a start/end element can be either a place or a transition. The authors prove that “folding” a WF-net based on an identified component, under certain conditions, yields a sound WF-net. The folding operator for components as defined in [20] can be regarded as being very similar to the
reduction (cf. Definition 9) presented in this paper. However, note that the proofs in [20] only hold for components, i.e., subnets with a single entry and exit. The algorithm described in [20] is similar to the algorithm presented in this paper, i.e., searching and replacing patterns until either a WF-net with a single transition is found, or no more pattern is found. However, within the algorithm, a specific ordering for the patterns and a maximization of the pattern-size is applied. Observe that, whereas [20,21] is conceptually close to the work presented here, there are several differences as well. For example, in this work, we use system nets to represent patterns, i.e., lifting the single source/sink requirement for pattern recognition. As such, the algorithm presented in this paper is able to detect process tree fragments in WF-nets, in which the algorithm reported on in [20,21] would not find any fragments. Similarly, the algorithm presented in this paper does not impose any order on the reduction of the patterns identified, nor on their size. However, there is no clear motivation provided in [20] on the underlying reasons for imposing an order and maximization w.r.t. pattern detection.

In [22,23] the notion of the Refined Process Structure Tree (RPST) and its computation is introduced. The RPST is a hierarchical grouping of the edges present in a process model (defined as a workflow graph). As such, the given process model can be decomposed, i.e., on the basis of the hierarchy described by the RPST. Similar to [20,21], the identified model-fragments need a single source and a single sink element. The works [22,23] exemplify computing the RPST of a given BPMN model (which complies with the definition of the workflow graphs mentioned earlier), yet, indicate that the concepts can be generalized to WF-nets. However, as we show in Section 6.2, the fact that the RPST, by definition, ignores the semantics of the model provided as an input, leads the algorithm to find tree structures in unsound Workflow nets. The RPST decomposition has been exploited in various noteworthy other studies. In [24,25], the authors use the RPST to “structure acyclic process models”. The core idea is to compute an RPST decomposition of a given acyclic model, which is possibly unstructured. An unstructured part of the model is recognized as a rigid component in the RPST decomposition. Subsequently, the behavioral ordering relations of the rigid component are computed, and a corresponding structured process model is synthesized. Since there exist process models that do not have an equivalent well-structured representation, the aforementioned work is further extended in [26], in which the authors exploit the RPST decomposition to compute a maximally structured version of the input process model. In [27], the authors extend the notion of RPSTs for sound free-choice WF-nets, i.e., referred to as a WF-tree. Within a WF-Tree, certain internal vertices can be labeled as being either place-bordered, transition-bordered, or as a loop construct. As such, the authors partially annotate the RPST with behavioral information. Whereas the RPST is computed on the basis of a tree of triconnected components, other similar tree-based abstractions of process models have been considered as well. In [28], the authors propose to exploit the tree of biconnected components to check whether a given workflow net is sound on the basis of its structure. In particular, the authors show that it is sufficient to show that one biconnected subnet of the workflow net is not safe and sound, to conclude that the WF-net as a whole is not sound.

The reductions presented in this paper, alternatively to the different works on translating process modeling formalisms into each other, bear similarity to various reduction rules established on general Petri nets. The general idea of Petri net reduction (or the opposite, expansion) is a substitution of elements of a Petri net, i.e., either by a smaller or larger newly added subnet, while preserving the behavioral properties of the net. For example, in [29], the authors propose step-wise refinements of both transitions and places in Petri nets, while preserving liveness and boundedness properties of the Petri net. Similarly, in [30], the author propose a set of reduction rules for Colored WF-nets, i.e., WF-nets with additional data flow semantics. In [31], the authors present a set of reduction rules for free-choice probabilistic WF-nets, i.e., WF-nets in which transitions have an associated probability and reward. In particular, the reduction rules are proposed in order to preserve the expected reward of the workflow.

Clearly, the work presented in this paper bears similarity with the different works mentioned. However, the works in the area of process model transformation are typically not defined for WF-nets,
6. Discussion

In this section, we discuss various aspects of the algorithm proposed in this paper. Firstly, i.e., in Section 6.1, we discuss the degree of extensibility of the framework, e.g., we discuss the detection of self-loops. Secondly, i.e., in Section 6.2, we provide an in-depth discussion of the relation of the proposed algorithm w.r.t. computation of the RPST decomposition. Finally, in ??, we discuss the reducibility of arbitrary WF-nets in the context of our proposed algorithm, i.e., we show an example of simple sound WF-nets for which the algorithm cannot find a corresponding process tree.

6.1. Extensibility

Since correctness of the proposed algorithm (cf. Theorem 1) holds for any feasible pattern (cf. Definition 8) that is globally language preserving, the algorithm presented in this paper is easily extended with additional reduction rules. Hence, any system net that describes a language that is equal to the language of a process tree can be reduced (conditional to the aforementioned global language preservation). For example, consider the self-loop reduction visualized in Fig. 14 and defined in Proposition 5.

Proposition 5 (\(\bigcirc_x\)-Pattern (Self-Loop)). Let \(N=(P,T,F,\kappa)\in\mathcal{N}_Q\) and let \(T'\subseteq T\ (|T|\geq 1)\). If and only if:

1. \(\forall t,t'\in T' (\bullet t=\bullet t'\Rightarrow \bullet t' t'=t' \bullet)\); all transitions are self-loops on the same set of places,

then, system net \(SN=(N'=(P',T',F',\kappa_{|T'}), \bullet T, T \bullet)\), with \(P=\bullet T, F=\{(x,y)\in F \mid x\in T' \vee y\in T'\}\), is a feasible \(\bigcirc_x\)-pattern.

Observer that, applying the reduction as defined in Definition 9, again yields a self-loop. Hence, in the reduction, we split-up the places, i.e., one group of places, forming the preset of the newly generated transition \(t'\) copies all incoming arcs of the places of the pattern (excluding the connections to \(t_1, ..., t_2\)). The other “freshly” added place copies all outgoing arcs of the places of the pattern (again excluding the connections to \(t_1, ..., t_2\)).

Consider Fig. 15, in which we depict a simple example of the application of the self-loop reduction as described. The transitions \(t_2\) and \(t_3\) in the WF-net depicted in Fig. 15a are self-loops on place \(p_1\). In Fig. 15b, the reduction is applied only on \(t_2\). Note that, in this model, a loop reduction can be applied yielding \(\bigcirc (\bigcirc (\tau, b), c)\). Note that, first reducing \(t_3\) is symmetrical, i.e., eventually yielding \(\bigcirc (\bigcirc (\tau, c), b)\). Note that both process trees, indeed, describe the language \((b^*c^*)^+\) (i.e., when described as a regular expression). In Fig. 15c, we show the application of the self-loop reduction when it is applied directly using \(T=\{t_2, t_3\}\). In this case, the reduction yields a new transition \(t'_2\) with label e.g., the RPST decomposition, or are more restrictive on the patterns to be replaced, e.g., the maximized unique source/sink patterns of [20]. Similarly, whereas the reduction patterns defined here do preserve the soundness of the WF-net, i.e., if the given WF-net is sound, the core of the related work in the field focuses more on the preservation of various behavioral properties.
638 646 637 653 652 651 649 648 645 643 642 641 640 639 635 632 631 630 629 628 627 626 625 623 622 621 620 624 WF-net depicted in Fig. 15a. (c) Self-loop reduction where \( T' = \{t_2, t_3\} \).

Figure 15. Example application of the self-loop pattern reduction.

620 \( \circ \ (\tau, \times (b, c)) \). Again, the language described by the process tree discovered can be described by \( (b^*c^*)^* \). Finally, let \( X \) denote any of the three process tree fragments discoverable in the example describing \( (b^*c^*)^* \). Observe that the reduction algorithm discovers \( \rightarrow (a, X, d) \) (or any binary form thereof), which corresponds to the regular expression \( a(b^*c^*)d \), which is indeed the language of the WF-net depicted in Fig. 15a.

Observe that the self-loop pattern shows that the algorithm proposed is extensible. However, in this case, the reduction step needs to be altered to avoid iteratively adding self-loop places (i.e., indefinitely). Any pattern can be reduced, i.e., as long as it is a feasible pattern that is globally language-preserving. For example, in some cases, the \emph{inclusive} or operator is considered in the context of process trees, i.e., \( \lor (Q_1, ..., Q_n) \). An inclusive or structure dictates that at least one of its children \( Q_1, ..., Q_n \) is executed, yet, possibly, all are executed. The order in which the children are executed is irrelevant. Similarly, the \emph{interleaved} operator is sometimes considered, i.e., \( \leftrightarrow (Q_1, ..., Q_n) \). This operator requires that all its children are executed in any order, however, the behavior of the respective children cannot be shuffled, i.e., this is allowed by \( \land (Q_1, ..., Q_n) \). Since both operators have a translation to a Petri net structure, these patterns can serve as a basis for reduction (potentially in a generalized form).

However, note that these patterns are more involved w.r.t. the four basic patterns (and the self-loop pattern) presented in this paper.

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However, note that these patterns are more involved w.r.t. the four basic patterns (and the self-loop pattern) presented in this paper.

626 Relation to Refined Process Structure Tree

One of the works that is conceptually very close to the work presented in this paper, is the work on the Refined Process Structure Tree (RPST) [22,23]. An RPST describes a hierarchy of sub-workflows of a \emph{workflow graph}, such that each sub-workflow represents a connected subgraph with a single entry and single exit of control. In this context, a workflow graph is simply a two-terminal graph (TTG), i.e., a directed graph without self-loops with a unique source \( s \) and sink node \( t \), s.t. each node in the TTG is on a path from \( s \) to \( t \). Note that a WF-net, i.e., from a graph-theoretical perspective, is a workflow graph. However, various other process modeling formalisms, e.g., BPMN, are also considered a workflow graph. Hence, an RPST can be computed on a much wider variety of process modeling formalisms, i.e., compared to the approach presented in this paper.

Formally, given a workflow graph \( G_W = (V, E, w) \) (a multi-graph in which \( w \) assigns each edge in \( E \) to an ordered pair of nodes) an RPST is a hierarchy of \emph{fragments}. A fragment is a subset \( E' \subseteq E \) of arcs, s.t., the subgraph formed by \( E' \) (including their incident vertices) is connected. Furthermore, the fragment should only contain one unique \emph{entry vertex} and one unique \emph{exit vertex}. A vertex is an entry vertex iff none of its incoming arcs are part of \( E' \) or all of its outgoing arcs are part of \( E' \). A vertex is an exit vertex iff none of its outgoing arcs are part of \( E' \) or all of its incoming arcs are part of \( E' \). The RPST of a workflow graph is the set of canonical fragments, i.e., those fragments that completely contain
other fragments or are completely contained by other fragments, i.e., any overlap between fragments is not allowed. In [23], the authors show that computation of an RPST is equivalent to computing the tree of triconnected components on a normalized variant of $G_W$.

Clearly, each individual edge of a workflow graph is a fragment. Similarly, the complete set of arcs $E$ defines a fragment. As an example, consider Fig. 16, in which we present a simple example WF-net (Fig. 16a) and its corresponding RPST decomposition (Fig. 16b and Fig. 16c). The edges $(p_i, t_1)$ and $(t_1, p_1)$, visualized as $e_1$ and $e_2$ are part of the root fragment, i.e., $F_0$, which is the complete edge set of the WF-net/workflow graph. The choice construct, i.e., connecting place $p_1$ and $p_0$ to transitions $t_2$ and $t_3$ respectively, comprises fragment $F_1$, which is further subdivided into fragments $F_2$ and $F_3$.

Note that, the process tree corresponding to $W_2$ is $\rightarrow (a, \times (b, c))$, i.e., consisting of 5 vertices. Hence, to translate the RPST to the corresponding process tree, we need to “collapse” $F_2$ and $F_3$ into $b$ and $c$ respectively. Similarly, $F_1$ needs to be transformed to $\times$, and, $F_0$ needs to be transformed to $\rightarrow$. Finally, $e_1$ and $e_2$ need to be merged into $a$.

The previous example illustrates that there is no general direct correspondence between the RPST of a WF-net and a corresponding process tree that describes the same language. Furthermore, it shows that translation of the RPST to a process tree is a non-trivial operation. As the RPST decomposition ignores the semantics of a WF-net, i.e., contributing to its more general applicability w.r.t. the algorithm presented in this paper (only applicable to process models that can be transformed into a WF-net), it also exists for WF-nets that are unsound.

Due to the generic nature of the RPST, i.e., it defines a graph-theoretical property of a workflow graph, it (largely) ignores the semantics and graph-theoretical properties of Petri nets. In particular, as an activity in a BPMN model only consists of a single entry and exit arc, within the underlying workflow graphs these activities are simply presented as a single edge. Since transitions in Petri nets represent process activities, and, transitions are able to have multiple incoming and outgoing arcs, transitions in a WF-net cannot be represented as a single arc in the corresponding WF graph.

For example, consider Fig. 16, in which we show the RPST of a WF-net that is not well-handled, i.e., $t_1$ generates concurrent behavior, place $p_3$ merges both branches of concurrent behavior. Since the RPST decomposition is not aware of the conceptual difference between places and transitions, the RPST subdivides the graph into several fragments. However, this is rather inconvenient, since the WF-net is not sound at all. Hence, from the RPST decomposition itself, one cannot judge whether a corresponding process tree exists.

The reverse is also possible, i.e., given a WF-net with a corresponding process tree representation, finding an RPST can be challenging. For example, when computing the RPST of the running example

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8 Normalization is performed by splitting vertices with multiple different incoming and outgoing edges into two nodes.
used in this paper, i.e., Fig. 2, the behavior formed by the loop transition \( t_6 \) cannot be decomposed into smaller chunks.\(^9\) Observe that the algorithm proposed in this paper is able to find the loop behavior due to the simplification of the reduction steps executed prior to the loop detection in Fig. 5c.

Note that the aforementioned examples are not intended to disqualify the application of the RPST decomposition for the purpose of transforming WF-nets to process trees. However, they merely indicate that using the RPST decomposition as a basis for such translation is not a trivial adoption.

### 6.3. Reducibility of WF-Nets

Thus far, we have considered various system net based patterns that we reduce into a corresponding process tree notation. We have shown that if the algorithm returns a WF-net with a specific structure, its label captures a process tree describing the same language as the original WF-net. However, it remains an open question what class of WF-nets are guaranteed to result in a process tree.

Since the basic operators considered in this paper all correspond to free-choice WF-nets, i.e., WF-nets s.t., \( \forall p \in P : (|p\cdot| = 1 \lor \bullet(p\cdot) = \{p\}) \) (a place either has one outgoing arc, or it is the sole incoming arc of all transitions it connects to). Hence, intuitively, we suspect that the class of free choice nets always yields a corresponding process tree.

However, consider Fig. 18, in which we depict a free-choice WF-net, which the proposed algorithm is not able to reduce. Observe that the model consists of two concurrent branches, i.e., enabled by transition \( t_1 \). However, execution of transition \( t_5 \) is conditional to execution of \( t_2 \), i.e., firing both \( t_2 \) and \( t_2 \) enables transition \( t_5 \). One can look at this type of condition, i.e., induced by place \( p_7 \), as a non-local behavioral relation. There is interaction between members of the “upper part” and the “lower part” of the concurrent construct. Such a type of interaction cannot be modeled using a tree-based process modeling formalism.

Based on the previous example, we conclude that any class extending free-choice Petri nets might represent various WF-nets that cannot be reduced by the algorithm proposed. The notion of block-structured WF-nets seems to be an adequate subclass of free-choice WF-nets that can always be reduced by the model, i.e., they are often used interchangeable with process trees. However, an exact

\(^{9}\) In terms of RPST, the loop structure is generating a rigid fragment.
structural definition of said class of WF-nets does not exist in literature (yet). For example, in [16],
an informal description of block-structured WF-nets is proposed: “A workflow net is block structured
if for every place or transitions with multiple outgoing arcs, there is a corresponding place or transition with
multiple incoming arcs. The parts of the net between the outgoing and incoming arcs form regions, and no arcs
can exist between regions, i.e. the regions have a single entry and a single exit.” However, transforming said
description into a formal, graph-theoretical property, is not trivial for cyclic models.

7. Conclusion

In this paper, we presented an algorithm to construct a process tree on the basis of a Workflow net
(WF-net). The proposed algorithm replaces fragments of the WF-net that correspond to a process tree
operator, i.e., by means of reduction rules. If the algorithm reduces the WF-net into a net, containing just
one transition, there exists a corresponding process tree for the given WF-net, with the same language.
The reduction rules proposed are bidirectionally soundness preserving. Hence, in case a process
tree is found, the original WF-net is sound. We have conducted experiments using a prototypical
implementation, indicating quadratic time complexity in the net and process tree rediscoverability.

Future Work We aim to extend the work presented in this paper in the following directions. We
aim to provide diagnostics w.r.t. the reason why a given WF-net cannot be reduced further, e.g., by
assessing if removal of certain elements of the WF-net allows for further reduction. Alternatively,
it is interesting to “wrap” certain fragments of the net into an encapsulating transition, after which
the search to process tree fragments is continued. Another interesting direction, as briefly discussed
in Section 6, is the search for structural properties of WF-nets that directly indicate whether a given
WF-net corresponds to a process tree.

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