Maximal Structuring of Acyclic Process Models

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This article addresses the transformation of a process model with an arbitrary topology into an equivalent structured process model. In particular, this article studies the subclass of process models that have no equivalent well-structured representation but which, nevertheless, can be partially structured into their maximally-structured representation. The transformations are performed under a behavioral equivalence notion which preserves the observed concurrency of tasks in equivalent process models. The article gives a full characterization of the subclass of acyclic process models that have no equivalent well-structured representation but do have an equivalent maximally-structured one, as well as proposes a complete structuring method. Together with our previous results, this article completes the solution of the process model structuring problem for the class of acyclic process models.

Keywords: Process modeling; structured process model; maximal structuring; model transformation; fully concurrent bisimulation

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1. INTRODUCTION

Process models have become the key design artifacts in Business Process Management (BPM) [1, 2]. They are used to design new processes, document existing processes, discuss process improvement, and last but not least, drive process executions in Process-Aware Information Systems (PAIS) [3]. Their dual role as executable code and as means of communication among process stakeholders has raised debates and concerns about how a particular process should be represented in a process model. In summary, execution and analysis favor, or even demand, specific structural properties which are hard to adhere to when creating process models. This renders the transformation of arbitrary unstructured models into equivalent well-structured models a highly relevant problem [4, 5, 6]. This article extends the technique for structuring acyclic process models [6] with an approach for maximal structuring of inherently unstructured process models, i.e., a process model that has no equivalent well-structured representation gets partially structured to the point where it cannot be structured further.

A process model is usually represented as a graph, where nodes stand for tasks or decisions, and edges encode causal dependencies between adjacent nodes. Common process modeling notations, such as the Business Process Model and Notation (BPMN) [7] or Event-driven Process Chains (EPC) [8], allow process models to have almost any topology. Structural freedom allows for a large degree of creativity when modeling. Nevertheless, it is often preferable that models follow certain structural patterns. The arguably most-agreed on structural property of process models is structuredness [4].

A process model is (well-)structured, if for every node with multiple outgoing arcs (a split) there is a corresponding node with multiple incoming arcs (a join), and vice versa, such that the fragment of the model between the split and the join forms a single-entry-single-exit (SESE) process component; otherwise the model is unstructured.

Figure 1(a) shows a process model. In the figure, every dotted box defines a process component composed from the arcs that are inside or intersect the box. Split u has a corresponding join z; together they define SESE component R1. Yet, splits v and w have no corresponding joins and, thus, the model in Figure 1(a) is unstructured. Figure 1(b) shows a well-structured process model, which is equivalent to the model in Figure 1(a). Every split of the model has a corresponding
The motivations for well-structured process modeling are manifold: (i) Structured models are easier to comprehend and tend to have fewer errors than unstructured ones [11]; (ii) By transforming unstructured process models to structured ones, one extends the applicability of process analysis techniques which are only applicable for structured models [12, 13, 14] to a larger class of models and improves translations between models captured in different languages [15, 16, 17]; (iv) Structured process models are preferred in the context of refactoring large process model repositories [18, 19, 20]; (v) Structured process models are better suited for optimization [21]; Etc. Consequently, some process modeling languages urge for structured modeling, e.g., Business Process Execution Language (BPEL) [22] and ADEPT [23, 24]. However, a modeling methodology that confines itself to “structured” languages faces certain limitations: (i) There exist process models that have no equivalent well-structured version [4] (this simply means that certain processes cannot be modeled); (ii) Structured modeling implies design time constraints and, thus, limits creativity of process model developers. Process modeling is carried out by humans who undergo creative practices. Different people can come up with different solutions to capture the very same process, for example the two process models in Figure 1. Enforcement of structured modeling can lower productivity of a developer. We advocate for modeling without limitations. The modeling language should provide process model developers with a maximal degree of structural freedom to describe processes. Afterwards, scientific methods can propose (upon request and whenever possible) alternative formalizations that are “better” structured, preferably well-structured. Therefore, one should be allowed to specify the model as in Figure 1(a) and, if requested, the equivalent structured model, as in Figure 1(b), should be constructed automatically. Alternatively, unstructured models can result from model synthesis techniques such as process mining [25]; structuring can then be applied to improve the readability of the mined models.

In a previous work [6], we proposed a technique to automatically transform acyclic process models with arbitrary topologies into equivalent well-structured models. The structuring is accomplished under a notion of behavioral equivalence called fully concurrent bisimulation [26].\footnote{The fully concurrent bisimulation corresponds to other equivalence notions developed independently in contexts of different models for concurrence, e.g., the history preserving bisimulation for event structures [27] and BS-bisimulation for behavior structures [28].} Among numerous existing notions of behavioral equivalence [29] proposed for different models for concurrence [30], the fully concurrent bisimulation is founded on the “strongest” concurrency semantics that allows preserving concurrency of observable tasks and ignoring the impact of invisible operations [31]. As an outcome of structuring reported in [6], the resulting well-structured models describe the same share of concurrency as the original unstructured models, etc., as shown in the structuring scenario in Figure 1(a). Note that in the following, in the context of model structuring
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practice, we shall often refer to fully concurrent bisimilar models as equivalent models.

It was shown in [4] (by means of a single example) and confirmed in [6] (for the general case of acyclic models) that there exist process models that do not have an equivalent well-structured representation. Figure 2(a) is an example of a model which has no equivalent well-structured version. Though not completely structurable, the model can be partially structured to result in its maximally-structured version. Intuitively, maximal structuring should be understood as follows.

A process model \( P \) is maximally-structured, if every process model that is equivalent to \( P \) has at most the same number of SESE components defined by pairs of split and join nodes as \( P \).

Here, SESE components composed of a single arc or a sequence of arcs, are ignored during comparison as they, in isolation, do not contribute to structural complexity. Figure 2(b) shows a maximally-structured version of the model in Figure 2(a). Though not well-structured, the model in Figure 2(b) is “better” structured than its equivalent model in Figure 2(a). The maximally-structured model has two SESE components \( B1 \) and \( R1 \) defined by the split-join pairs \((q, r)\) and \((s, z)\), respectively, as compared to one component \( R1 \) defined by the split-join pair \((n, z)\) in Figure 2(a). Moreover, there exists no process model which describes the same process as the models in Figure 2 and shows more structure, that is, has more SESE components.

After the initial investigations in [32], this article gives for the first time a complete solution to the problem of maximal structuring of acyclic process models. We characterize the class of acyclic process models which do not have an equivalent well-structured representation, but which can, nevertheless, be maximally-structured; and we provide a complete structuring method. Together with the results in [6], this article completes the structuring technique for the class of acyclic process models.

Figure 3 visualizes the overall setting of the process model structuring problem. In that figure, region APM represents the set of all Acyclic Process Models, where every dot inside the region represents a model: \( p_1, p_2, \) and \( p_3 \) represent process models which are subjects for structuring. The behavioral equivalence relation is an equivalence relation on APM [26]. \( C_1, C_2, \) and \( C_3 \) are the equivalence classes of the behavioral equivalence relation that contain models \( p_1, p_2, \) and \( p_3, \) respectively. Every equivalence class contains the set of all behaviorally equivalent process models. The task of structuring is to answer the question whether an equivalence class contains a model which is “better” structured than a given one from the same class, preferably a well-structured one. In our example, class \( C_1 \) contains well-structured model \( s_1 \) (e.g., \( C_1 \) is the class which contains the models from Figure 1), class \( C_2 \) contains no well-structured but a maximally-structured model \( m_1 \) (e.g., \( C_2 \) is the class with the models from Figure 2), whereas class \( C_3 \) contains no models which exhibit more structure than model \( p_3 \) and, thus, \( p_3 \) is inherently unstructured. In this article, we give an answer to the problem of structuring acyclic models.

The remainder of this article proceeds as follows. The next section discusses related work on structuring sequential programs and process models. Afterwards, Section 3 gives preliminary definitions which we shall use later to convey our findings. In Section 4, we formally define the “well-structured” property of process models. Section 5 discusses the structuring technique proposed in [6]. The technique is summarized as a chain of transformations. We define for the first time the notion of the proper complete prefix unfolding which was sketched in [6] and which is essential for obtaining sufficient behavioral information to allow maximal structuring. Section 6 motivates and defines the “maximally-structured” property of process models. Afterwards, Section 7 extends the structuring technique from Section 5 for maximal structuring of process models that do not have an equivalent well-structured representation. Section 8 presents an empirical evaluation of the structuring method on a set of process models taken from industrial practice. Finally, we draw conclusions.

2. RELATED WORK

Our setting is close to the problem of structuring flowcharts and sequential programs, which has been extensively studied for years. In one of his letters, Edsger W. Dijkstra started a discussion with a provocative title “Go To Statement Considered Harmful” [33]. In the absence of Go To statements, programs are composed of structured flow constructs only, situation that corresponds to our notion of well-structured process models without concurrency constructs. The main idea communicated in the letter is that in the context of sequential programs the Go To statement should be abolished from all “higher level” programming languages. Since that time, many replies to the letter...
supported or rejected the statement of Dijkstra, for instance [34, 35, 36, 37], with no side being able to provide sound arguments to disarm one another. The partial resolution of the conflict became possible due to many works on formal techniques for translating unstructured programs with Go To statements into equivalent structured programs [38, 39, 40, 41]. The main outcome of these endeavors is that any sequential program can be structured with only one control flow pattern, viz. forward jump from a loop, requiring introduction of fresh control variables in structured programs [40]; other flow patterns can be structured by employing code duplications and structured control flow constructs like if-then-else or while-do.

The results on structuring sequential programs do not hold for process models which comprise concurrency. One of the earliest studies on the problem of structuring process models is that of Kiepuszewski et al. [4]. The authors showed that not all acyclic process models can be structured by putting forward a counter-example, which essentially boils down to the one in Figure 4 (also known as Z-structure, due to the configuration of causal relations between the tasks). The authors showed that there is no well-structured process model that is equivalent to this one under the fully concurrent bisimulation equivalence notion. They do explore some causes of unstructuredness, but neither give a full characterization of the class of models that can be structured, nor do they define any automated transformation.

![Process model (Z-structure)](image)

FIGURE 4. Process model (Z-structure)

Some work has been devoted to the characterization of sources of unstructuredness in process models. In [5], the authors present a taxonomy of unstructuredness, that covers acyclic and cyclic models. The taxonomy is based on the notion of improper nesting and mismatched pairs. The taxonomy allows to analyze unstructured process models, determine whether they are well-behaved, and whether they can be transformed into equivalent structured models. However, the taxonomy is incomplete, as it does not cover all possible cases of process models that can be structured. Besides, the authors do not define an automated algorithm for structuring unstructured process models.

Other methods simply reuse techniques for structuring flow charts and sequential programs in order to partly structure process models. [42] proposes a method for structuring sequential parts of a process model based on Go To program transformations, and extends this method to process graphs where concurrent parts are already structured. This method cannot deal with process models which comprise unstructured concurrent threads of control. A similar remark applies to [43], where authors concentrate on structuring of unstructured cyclic flows. In [44], a translation from (unstructured) Petri nets to (structured) BPEL processes is proposed. While the proposed method can handle unstructured concurrent threads of control, it does so by directly expressing them in terms of BPEL’s flow activity and links. Put differently, the method identifies the already structured parts of the process model, but provides no means for structuring the unstructured parts. In [45], the authors outline a classification of process components (parts of process models) using region trees. The authors mention that region trees can be employed to transform unstructured process models into well-structured ones, however they do not provide a structuring method, even for acyclic models. In [46], the authors study the influence of “hidden” unstructuredness in process models on their correctness.

Table 1 summarizes related work on structuring techniques [40, 4, 5, 6] and illustrates contributions of this article. Columns of the table correspond to different techniques, whereas rows correspond to different levels of process model expressiveness and its structural properties. The structuring problem is solved for flow charts/sequential programs (xor logic, acyclic or cyclic), e.g., refer to [40] (see the “+” sign in the first row, first column). For this class of models, the structuring problem is equivalent to the problem of GOTO elimination in the theory of programming languages and compiler optimization. It is well-known that every sequential algorithm can be captured in a well-structured program [47], or otherwise transformed into a well-structured program [40]. The problem addressed in this paper is harder than structuring flow charts/sequential programs as process models combine sequential control-flow with concurrency. First partial solutions for structuring of process models with concurrency (and only and mixed xor/and logic, acyclic or cyclic) were proposed in [4, 5]. These two techniques took different approaches to classify sources of unstructuredness, but they do not provide the complete characterization, see the “o” signs in the table. The

| TABLE 1. Contribution of this article (•) in the light of our previous work and related work on fundamental structuring techniques; – (no structuring), o (partial structuring), + (complete structuring) |
|-------------------------------------------------|-----|-----|-----|-----|-----|
| xor (flow charts/programs)                     | 40  | 4   | 5   | 6   | •   |
| and (well-struct.)                             | –   | o   | o   | +   | +   |
| and (inh. unstr.)                              | –   | o   | o   | +   | +   |
| and (maximal)                                  | –   | –   | –   | –   | +   |
| xor/and acyclic (well-struct.)                 | –   | o   | o   | +   | +   |
| xor/and ac. (inh. unstr.)                      | –   | o   | o   | +   | +   |
| xor/and ac. (maximal)                          | –   | –   | –   | –   | +   |
| xor/and cyclic                                 | –   | o   | o   | –   | –   |
technique proposed in [6] completely structures acyclic process models with xor/and logic that have a well-structured representation and it is capable of recognizing inherently unstructured process models. All mentioned techniques fail on structuring models with xor/and logic that are inherently unstructured but have parts that can be structured, i.e., they fail to achieve maximal structuring. The technique proposed in this article addresses this problem for acyclic models. Note that xor only structuring, e.g., [40], is reused by other techniques including the one in this article, whenever components with xor only logic occur, see the “−” signs in the first row and the first column of the table.

To sum up, to the best of our knowledge, existing techniques approach structuring of process models with concurrency rather superficially. Existing structuring techniques either drop the requirement of preserving concurrency described in the unstructured process model, or the “problematic” parts of the process model are not structured at all and, hence, unstructuredness remains in the resulting process model. The technique proposed in this article allows to overcome these shortcomings.

3. PRELIMINARIES

In this section, we introduce some formal notions that will be used later to convey findings.

3.1. Process Models and Nets

In the introduction, process models were presented in a rather informal way. This section introduces all subsequently required formal notions on process models.

**Definition 3.1 (Process model).** A process model $P = (A,G,C,type,A,\mu)$ has a non-empty set $A$ of tasks, a set $G$ of gateways, $A \cap G = \emptyset$, and a set $C \subseteq (A \cup G) \times (A \cup G)$ of control flow arcs of $P$; type: $G \to \{\text{xor}, \text{and}\}$ assigns to each gateway a type; $\mu: A \to A$ assigns to each task a name from $A$, $\tau \in A$.

$A \cup G$ are the nodes of $P$; a node $x \in A \cup G$ is a source (sink), iff $\bullet x = \emptyset (x \bullet = \emptyset)$, where $\bullet x$ ($x \bullet$) stands for the set of immediate predecessors (successors) of $x$. We assume $P$ to have a single source and a single sink; both are tasks. For a task $a \in A$, if $\mu(a) \neq \tau$, then $a$ is observable; otherwise, $a$ is silent. Every node of $P$ is on a path from the source to the sink. Each task $a \in A$ has at most one incoming and at most one outgoing arc, i.e., $|\bullet a| \leq 1 \land |a \bullet| \leq 1$. Each gateway $g \in G$ is either a split ($|\bullet g| = 1 \land |g \bullet| > 1$) or a join ($|g \bullet| > 1 \land |g \bullet| = 1$).

We adopt a notation similar to BPMN for visualizing process models as shown in Figures 1 and 2: a round rectangle represents a task, the name is inscribed; a 45°-rotated square represents a gateway, an inscribed $+$ denotes an xor (and) gateway. The round nodes $i$ and $o$ in Figure 1(a) are silent tasks. Their role is rather technical: to ensure the existence of the source and sink tasks. The semantics of process models is defined by a mapping to Petri nets.

**FIGURE 5.** Mapping process models to nets (note that tasks can be silent as well)

**Definition 3.2 (Petri net).** A Petri net, or a net, $N = (P,T,F)$ has finite disjoint sets $P$ of places and $T$ of transitions, and the flow relation $F \subseteq (P \times T) \cup (T \times P)$.

For a node $x \in P \cup T$, $\bullet x = \{y \mid (x,y) \in F\}$ is the preset, whereas $x \bullet = \{y \mid (y,x) \in F\}$ is the postset of $x$; $Min(N)$ denotes the set of nodes of $N$ with an empty preset. A node $x \in P \cup T$ is an input (output) node of a node $y \in P \cup T$, iff $x \in \bullet y$ ($x \in y \bullet$). For $X \subseteq P \cup T$, let $\bullet X = \bigcup_{x \in X} \bullet x$ and $X \bullet = \bigcup_{x \in X} x \bullet$. For a binary relation $R$ (e.g., $F$ or $C$), we denote by $R^+$ the reflexive and transitive closure, and by $R^*$ the transitive closure of $R$.

In the following, we assume that all nets are $T$-restricted, that is, every transition of a net has at least one input and at least one output place. If this is not the case, we assume the natural completion of the net: the net gets modified so that a transition without an input (output) place gets a single input (output) place.

Often, it is useful to distinguish between observable and silent transitions of a net; this distinction can be made formal by labeling transitions. A labeled net $N = (P,T,F,\tau,\lambda)$ consists of a net $(P,T,F)$ and a function $\lambda: P \cup T \to T$ that assigns each node a label from $T$, $\tau \in T$. If $\lambda(t) \neq \tau$, then $t$ is observable; otherwise, $t$ is silent. We require all places of a labeled net to be silent, i.e., $\forall p \in P: \lambda(p) = \tau$.

Petri nets have precise execution semantics grounded on formal notions of states and state transitions, which are defined in terms of a “token game.” A state of a net is represented by a marking which describes a distribution of tokens on the net’s places. Whether a transition is enabled at a marking depends on the tokens in its input places. An enabled transition can occur, which leads to a new marking of the net.

Technically, we identify the flow relation $F$ with its characteristic function on the set $(P \times T) \cup (T \times P)$. Then, the semantics of nets can be formalized as follows.

**Definition 3.3 (Semantics).** Let $N = (P,T,F)$ be a net.

- $M: P \to N_0$ is a marking of $N$ assigning each place $p \in P$ a natural number $M(p)$ of tokens in $p$; $N_0$ is the set of natural numbers including 0. $[p]$ denotes the marking where place $p$ contains just one token.
and all other places contain no tokens. We identify 
M with the multiset containing M(p) copies of p, 
for every p ∈ P.
- For a transition t ∈ T and a marking M of N, t is
  enabled at M, written M[t], iff ∀p ∈ p.t : M(p) ≥ 1.
- If t ∈ T is enabled at M, then t can occur, which
  leads to a new marking M′ and the step M[t]M′ of
  N with M′(p) = M(p) − F(p, t) + F(t, p), p ∈ P.
- A net system, or a system, is a pair (N, M0), where
  N is a net and M0 is a marking of N. M0 is called
  the initial marking of N.
- A marking M is reachable in (N, M0), written
  M ∈ [N, M0], iff there exists a run of N, i.e., a
  sequence M0 = t0M1t1...Mn of steps of N that
  reaches Mn.

In this article, the structural subclass of free-choice nets
is particularly relevant to us. The free-choice property
ensures that if two transitions share an input place, 
then every reachable marking of the system enables either of these transitions or none of them [48, 49].

**Definition 3.4 (Free-choice net).** A net N = 
(P, T, F) is free-choice, iff ∀p ∈ P | p • > 1 : •(p) = (p).

Every process model (Definition 3.1) can be mapped to a corresponding labeled free-choice net with a special
structure, called WF-net [6, 50].

**Definition 3.5 (WF-net, WF-system).** A Petri net
N = (P, T, F) is a workflow net, or a WF-net, iff N
has a dedicated source place i ∈ P, with •i = Ø, N 
has a dedicated sink place o ∈ P, with •o = Ø, and the
short-circuit net N′ = (P, T ∪ {t′}, F ∪ {o, t′}, (t′, i)),
t′ ∈ T, of N is strongly connected. A WF-system is a
net system (N, M0), where M0 = [t].

The fact that the short-circuit net is strongly connected
guarantees that every node of the WF-net is on a
directed path from the source place to the sink
place [51]. Note that the results of this article are
independent of the specific mapping between process models and nets; they may differ in the amount of places and silent transitions but deliver the same result in
respect to branching structure and potential concurrent
enablement of observable transitions in the resulting
systems. Subsequently, we shall employ the mapping
from [6]; a process model is translated into a net
by transforming each of its control flow arcs to the
corresponding net fragment as shown in Figure 5.

The WF-net in Figure 6 corresponds to component 
R1 of the process model in Figure 1(a). Each task of
the model is mapped to a transition with its name as a label,
for instance λ(t2) = “Handle credit card payment”.
The empty boxes represent silent transitions labeled τ.
Note that silent tasks must be mapped to silent
transitions (not shown in Figure 5). The execution semantics of the resulting net system defines the semantics
of the process model. Note that when we refer to a net
without a marking as to a net system, we assume its

**FIGURE 6.** WF-net that corresponds to component R1 of
the process model in Figure 1(a)

natural initial marking that puts one token at every
place without incoming arcs and no tokens elsewhere.

Soundness and safeness are basic properties of WF-
systems [52]. Soundness states that every execution of a
WF-system ends with a token in the sink place, and once
there is a token in the sink place, no other tokens remain
in the net. Also, there should be no dead transitions, i.e.,
every transition should be able to occur in some
execution of the system. Safeness refers to the fact that
there is never more than one token in the same place.

**Definition 3.6 (Liveness, Safeness, Soundness).**
- A system (N, M0) is live, iff for every reachable
  marking M ∈ [N, M0] and t ∈ T, there exists a
  marking M′ ∈ [N, M], such that (N, M′)[t].
- A system (N, M0) is bounded, iff the set [N, M0]
  is finite. A system (N, M0) is safe, iff ∀M ∈ [N, M0] ∀ p ∈ P : M(p) ≤ 1.
- A WF-system (N, M0) with N = (P, T, F) is sound,
  iff the short-circuit system (N′, M0) is live and
  bounded, see [51, Theorem 1].

In our work, we require process models to be sound,
with the intuition that a process model is sound, iff its
corresponding WF-system is sound. As a sound free-
choice WF-system is guaranteed to be safe [51], the rest
of the article deals with sound and safe process models.

### 3.2. Unfoldings

An unfolding of a net system is another net that explicitly
represents all runs of the system in a possibly infinite,
tree-like structure [53, 54]. In [55], McMillan proposed
an algorithm to construct a finite initial part of the
unfolding, which contains full information about the
reachable markings of the system, viz. a complete
prefix unfolding. Next, we present main notions of the
theory of unfoldings, starting with ordering relations between
pairs of nodes in a net.

**Definition 3.7 (Ordering relations).** Let N = (P, T, F) be
a net and let x, y ∈ P ∪ T be two nodes of N.
- x and y are in causal relation, written x ∼N y, iff
  (x, y) ∈ F+. y and x are in inverse causal relation,
  written y ∼N x, iff x ∼N y.
- x and y are in conflict, x #N y, iff there exist
distinct transitions t1, t2 ∈ T, s.t. t1 ∩ t2 ̸= Ø, and
  (t1, x), (t2, y) ∈ F+. If x #N x, then x is in
  self-conflict.
- x and y are concurrent, x ∥N y, iff neither x ∼N y,
nor \( y \leadsto_N x \), nor \( x \not\leadsto_N y \).

The set \( R_N = \{ \leadsto_N, \nless_N, \nless_N, \mathbb{1}_N \} \) forms the ordering relations of \( N \).

In the following we omit subscripts of ordering relations where the context is clear. A structure of an unfolding is given by an occurrence net.

**Definition 3.8 (Occurrence net).** A net \( N = (B, E, G) \) is an occurrence net if, for all \( b \in B \) holds that \( e \in E \) iff \( e = b \in 1 \), \( N \) is acyclic, for each \( x \in B \cup E \) the set \( \{ y \in B \cup E \mid (y, x) \in G^* \} \) is finite, and no \( e \in E \) is in self-conflict.

The elements of \( B \) and \( E \) are called conditions and events, respectively. Any two nodes of an occurrence net are either in causal, inverse causal, conflict, or concurrency relation [56]. A branching process of a system \( S \) is an occurrence net where each event represents the occurrence of a transition of \( S \). The unfolding of \( S \) is simply its largest branching process.

The relation between \( S \) and its branching processes technically builds on a homomorphism that preserves the nature of nodes and the environment of transitions. Let \( N_1 = (P_1, E_1, F_1) \) and \( N_2 = (P_2, E_2, F_2) \) be nets. A homomorphism from \( N_1 \) to \( N_2 \) is a mapping \( h : P_1 \cup E_1 \rightarrow P_2 \cup E_2 \), such that: \( h(F_1) \subseteq F_2 \) and \( h(T_1) \subseteq T_2 \), and for all \( t \in T_1 \), the restriction of \( h \) to \( \bullet t \) is a bijection between \( \bullet t \) in \( N_1 \) and \( \bullet h(t) \) in \( N_2 \); correspondingly for \( \bullet t \) and \( h(t) \).

**Definition 3.9 (Branching process).** A branching process of a system \( S = (N, M_0) \) is a pair \( \beta = (N', \nu) \), where \( N' = (B, E, G) \) is an occurrence net and \( \nu \) is a homomorphism from \( N' \) to \( N \), such that:

- the restriction of \( \nu \) to \( \text{Min}(N') \) is a bijection between \( \text{Min}(N') \) and \( M_0 \), and
- for all \( e_1, e_2 \in E \) holds if \( e_1 = e_2 \) and \( \nu(e_1) = \nu(e_2) \), then \( e_1 = e_2 \).

The system \( S \) is referred to as the originative system of a branching process. The branching processes of \( S \) are ordered by their prefix relation.

**Definition 3.10 (Prefix relation).** Let \( \beta_1 = (N_1, \nu_1) \) and \( \beta_2 = (N_2, \nu_2) \) be two branching processes of a system \( S = (N, M_0) \). \( \beta_1 \) is a prefix of \( \beta_2 \) if \( N_1 \) is a subnet of \( N_2 \), such that: if a condition belongs to \( N_1 \), then its input event in \( N_2 \) also belongs to \( N_1 \), if an event belongs to \( N_1 \), then its input and output conditions in \( N_2 \) also belong to \( N_1 \), and \( \nu_1 \) is the restriction of \( \nu_2 \) to nodes of \( N_1 \).

A maximal branching process of \( S \) with respect to the prefix relation is called unfolding of the system. In [53], it is shown that every system has an (up to isomorphism) unique unfolding. Finally, a complete prefix unfolding of \( S \) is a special branching process of \( S \): it is obtained by truncating the unfolding at events where the information about reachable markings starts to be redundant.

**Definition 3.11 (Complete prefix unfolding).** Let \( \beta = (N', \nu), N' = (B, E, G) \), be a branching process of a system \( S = (N, M_0) \).

- A configuration \( C \) of \( \beta \) is a set of events, \( C \subseteq E \), such that: (i) \( C \) is causally closed, i.e., \( e \in C \) implies that for all \( e' \in E \), \( e' \leadsto e \) implies \( e' \in C \), and (ii) \( C \) is conflict-free, i.e., for all \( e_1, e_2 \in C \) holds \( e_1 \not\leadsto e_2 \).
- A local configuration of an event \( e \in E \) is the set of events that precede \( e \), written \( e] = \{ e' \in E \mid e' \leadsto e \} \).
- A set of conditions of an occurrence net is a co-set if its elements are pairwise concurrent. A maximal co-set with respect to the set inclusion is a cut.

Each finite configuration \( C \) of \( \beta \) induces the cut \( \text{Cut}(C) = (\text{Min}(N') \cup C) \cup \bullet C \) that represents the reachable marking \( \text{Mark}(C) = \nu(\text{Cut}(C)) \) of \( S \).

- \( \beta \) is complete if for each reachable marking \( M \) of \( S \) there exists a configuration \( C \) in \( \beta \), such that: (i) \( \text{Mark}(C) = M \), i.e., \( M \) is represented in \( \beta \), and (ii) for each transition \( t \) enabled at \( M \) in \( N \), there exists a configuration \( C \cup \{ e \} \) in \( \beta \), such that \( e \notin C \) and \( \nu(e) = t \).

- A partial order \( \prec \) on the configurations of \( \beta \) is an adequate order iff (i) \( \prec \) is well-founded, (ii) \( C_1 \subset C_2 \) implies \( C_1 \prec C_2 \), and (iii) If \( C_1 \prec C_2 \) and \( \text{Mark}(C_1) = \text{Mark}(C_2) \) then \( \prec \) is preserved for all finite extensions of \( C_1 \), i.e., the “future” after \( \text{Cut}(C_1) \) and \( \text{Cut}(C_2) \) is isomorphic, see [57] for details.

An event \( e \in E \) is a cutoff event induced by \( \prec \), iff there exists a corresponding event \( \text{corr}(e) = e' \in E \) such that \( \text{Mark}(e] = \text{Mark}(e'] \) and \( e' \prec e \).

- \( \beta \) is the complete prefix unfolding induced by \( \prec \), iff \( \beta \) is the greatest prefix of the unfolding of \( S \) that contains no event after a cutoff event.

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**Figure 7.** Complete prefix unfolding of the system in Figure 6

Figure 7 shows a complete prefix unfolding of the system in Figure 6. We write \( e_1, e_1', e_1'' \),... for conditions that are the occurrences of place \( p_2 \), correspondingly for events. In the prefix, event \( e_0 \) is a cutoff event, whereas event \( e_0 \) is its corresponding event; this relation is visualized by a dotted arrow. Both events reach the marking \( \{ x, y \} \) represented by the cuts \( \{ e_2, e_2' \} \) and \( \{ e_0, e_0' \} \), respectively. The size of the prefix depends on the “quality” of the adequate order used to perform the truncation. It has been shown that the adequate
order proposed in [57] results in more compact prefixes compared to the one suggested in [55].

4. WELL-STRUCTURED MODELS

In the introduction, we proposed an intuitive definition of the well-structured property of process models. In this section, we give a formal form to that intuition. We propose a structural classification for process models based on the properties of its parse tree. The Refined Process Structure Tree (RPST) is a technique to parse process models into a collection of its fragments, each with a single entry and single exit. The notion of the RPST fragment coincides with the notion of the SESE component used in the intuitive definition of a well-structured process model.

Let \( P = (A,G,C,\text{type},A,\mu) \) be a process model. A fragment of \( P \) is defined by a pair \((V,E)\) of nodes \( V \subseteq A \cup G \) and arcs \( E \subseteq C \), such that each arc in \( E \) connects only nodes in \( V \). A set \( F \subseteq C \) of arcs induces the fragment \( P_F = (V_F,F) \) formed by \( F \) where \( V_F \) is the smallest set of nodes such that \((V_F,F)\) is a fragment.

**Definition 4.1** (Interior, Boundary, Entry, Exit). Let \( P = (A,G,C,\text{type},A,\mu) \) be a process model and let \( P_F = (V_F,F) \) be a connected fragment of \( P \) that is formed by a set \( F \subseteq C \) of control flow arcs.

- A node \( x \in V_F \) is **interior** with respect to \( P_F \), iff it is connected only to nodes in \( V_F \); otherwise, \( v \) is a **boundary** node of \( P_F \).
- A boundary node \( v \) of \( P_F \) is an **entry** of \( P_F \), iff no incoming edge of \( v \) belongs to \( F \) or all outgoing edges of \( v \) belong to \( F \).
- A boundary node \( v \) of \( P_F \) is an **exit** of \( P_F \), iff no outgoing edge of \( v \) belongs to \( F \) or all incoming edges of \( v \) belong to \( F \).

A process component is a fragment of a process model with specific boundary nodes.

**Definition 4.2** (Process component). Let \( P = (A,G,C,\text{type},A,\mu) \) be a process model and let \( P_F = (V_F,F) \) be a connected fragment of \( P \) that is formed by a set \( F \subseteq C \) of control flow arcs. \( F \) is a **process component**, or a **component**, of \( P \), if \( P_F \) has exactly two boundary nodes: one is an entry and the other is an exit of \( P_F \).

By definition, the source of a process model is an entry to every component it belongs to, whereas the sink of a process model is an exit from every component it belongs to. In contrast to a fragment, we identify a process component only by its set of arcs. We say that two components \( F, F' \) are **nested** if \( F \subseteq F' \) or \( F' \subseteq F \). They are **disjoint** if \( F \cap F' = \emptyset \). If they are neither nested nor disjoint, we say that they **overlap**. The RPST of a process model is a collection of its special components, viz. **canonical** process components.

**Definition 4.3** (Canonical process component). Let \( P \) be a process model. A process component of \( P \) is **canonical**, if it does not overlap with any other process component of \( P \).

Finally, the RPST of a process model is composed of its canonical process components.

**Definition 4.4** (The refined process structure tree). The **refined process structure tree** (RPST) of a process model is the set of all its canonical process components.

It follows that any two canonical process components are either nested or disjoint and, thus, they form a compositional containment hierarchy. This hierarchy can be shown as a tree, where the parent of a canonical component \( F \) is the smallest canonical component that contains \( F \). Hence, the root of the tree is the entire model, whereas the leaves are the control flow arcs.

![Figure 8](image-url)

**Figure 8.** The (simplified) RPSTs of the process models of Figure 1

Every box with a dotted border in Figure 1 and Figure 2 defines a canonical process component which is composed of the arcs that are inside or intersect the box. Figure 8 shows an alternative visualization of the hierarchies of canonical process components, where every node represents a component and edges hint at the containment relation of components. Figure 8(a) and Figure 8(b) show (somewhat simplified) RPSTs of the process models in Figure 1(a) and Figure 1(b), respectively.

According to [58, Section 3.1], every canonical component of a process model belongs to one out of four structural classes. The names of the structural classes are borrowed from the types of the triconnected components of graphs, which are employed to construct the RPST, see [58] for details.

**Definition 4.5** (Component classes). Let \( F \) be a component of a process model \( P \).

- \( F \) is a **trivial** component, if \( F \) is singleton.
- \( F \) is a **polygon** component, if there exists a sequence \((r_0, \ldots, r_n)\), \( n \in \mathbb{N} \), of canonical components of \( P \), s.t., \( F = \bigcup_{i=0}^{n} r_i \), the entry of \( F \) is the entry of \( r_0 \), the exit of \( F \) is the exit of \( r_n \), and the exit of \( r_j \) is the entry of \( r_{j+1} \), \( 0 \leq j < n \).
- \( F \) is a **bond** component, if there exists a set \( R \) of canonical components of \( P \), s.t. \( F = \bigcup_{r \in R} r \) and every component in \( R \) has the same boundary nodes as \( F \).
A process model is well-structured if it possesses no rigid components, i.e., components that are neither a trivial, a polygon, nor a bond component.

The names of components in Figures 1, 2, and 8 hint at their structural class, e.g., $P1$ is a polygon, $B1$ is a bond, and $R1$ is a rigid component. In these figures, we do not explicitly show simple components, i.e., trivial components or polygons composed of two trivial components. Hence, we refer to the respective RPSTs as simplified ones. To exemplify the concepts, we refer to the models in Figure 1.

For instance, polygon $P1$ in Figure 1(a) is composed of two trivial components, $(i, u)$, and $(z, o)$, while bond $B1$ in Figure 1(b) is composed of the simple components, $P2$ and $P3$. Polygons $\{(u, a), (a, v)\}$, $\{(u, b), (b, w)\}$, $\{(w, c), (c, y)\}$, $\{(x, d), (d, z)\}$, $\{(y, e), (e, z)\}$ are the simple components inside rigid $R1$ in Figure 1(a). For a complete visualization of the RPST, the trees in Figure 8 have to be refined with these simple components.

The RPST of a process model is unique [59]. Moreover, the canonical components of a process model define all its SESE components, where non-canonical SESE components can be derived as subsets of polygons and bonds.

With all of the above, the well-structuredness property of a process model can be defined in terms of its RPST.

**Definition 4.6 (Well-structured model).**

A process model is well-structured, iff its RPST contains no rigid process component; otherwise, the model is unstructured.

The process model in Figure 1(b) contains no rigid components and is structured, while the process model in Figure 1(a) contains rigid $R1$ and is, therefore, unstructured.

In order to introduce the formal definition of the maximally-structured property of a process model, we need first to understand the structuring method proposed in Section 5 and its limitations. We return to maximal structuring in Section 6, where we take a closer look at the structuring scenario depicted in Figure 2.

5. **STRUCTURING**

This section discusses the technique for structuring acyclic process models from [6]. We elaborate further on the technique by proposing the notion of the proper complete prefix unfolding for the first time; we shall see that this type of prefix is essential to achieve maximal structuring.

![FIGURE 9. Structuring chain, see [6]](image)

Figure 9 shows the chain of phases that collectively compose the structuring technique. A process model first is decomposed into the hierarchy of its process components. Each component is a process model by itself and either well-structured or unstructured. An unstructured process component can in some cases be transformed into a well-structured one. For this purpose, the component is translated into a WF-system for which the ordering relations of its tasks are derived from its proper complete prefix unfolding. If the ordering relations have certain properties, the unstructured component can be replaced by a hierarchy of smaller well-structured components that define the same ordering relations. The equivalence of the resulting process model with the original unstructured one is guaranteed by the results presented in [60].

In the following, we present each phase of the structuring in detail. We employ the process model in Figure 1(a) to exemplify all structuring phases. Later, in Section 7, we extend the technique to allow maximal structuring.

5.1. **From process models to unfoldings**

A process model is well-structured, if and only if its RPST contains no rigid component (Definition 4.6). Therefore, an unstructured process model can be structured by traversing its RPST bottom-up and replacing each rigid component by its equivalent well-structured component. The difficult step is to find this equivalent well-structured component.

The key idea of structuring is to refine a rigid component $R$, i.e., a node of the RPST, by a subtree of well-structured RPST nodes which define the same behavioral (ordering) relations between the child RPST nodes of $R$. The first step for refining $R$ is to compute the ordering relations of $R$'s child nodes. We obtain these by constructing a complete prefix unfolding of $R$'s corresponding WF-system. The complete prefix unfolding captures information about all reachable markings of the originate system, but has a simpler structure as it is an occurrence net (Definition 3.8). To capture all well-structuredness contained in $R$, the complete prefix unfolding must have a specific shape, called proper.

**Definition 5.1 (Proper complete prefix unfolding).**

Let $\beta = (N', \nu)$, $N' = (B, E, G)$, be a branching process of an acyclic system $S = (N, M_0)$.

- A cutoff event $e \in E$ of $\beta$ induced by an adequate order $\xi$ is healthy, iff $\text{Cut}([e]) \cap \xi = \text{Cut}([\text{corr}(e)]) \cap \text{corr}(e)$.
- $\beta$ is the proper complete prefix unfolding, or the proper prefix, induced by an adequate order $\xi$, iff $\beta$ is the greatest prefix of the unfolding of $S$ that contains no event after a healthy cutoff event.

A proper prefix contains all information about well-structuredness, i.e., all paired gateways of splits and joins, in a rigid in the following way. A proper prefix $\beta$ represents each xor split as a condition with multiple post-events; each xor join is identified by the post-
conditions of a cutoff event \( e \) and its corresponding event. The notion of a cutoff event guarantees that \( \beta \) contains every xor split and join. An important observation here is that corresponding pairs of xor splits and joins are always contained in the same branch of \( \beta \). An and split manifests as an event with multiple post-conditions in \( \beta \), whereas an and join is an event with multiple pre-conditions. The healthiness requirement on cutoff events ensures that concurrency after an and split is kept encapsulated: when several concurrent branches are introduced in the unfolding they are not truncated until the point of their synchronization, i.e., the and join. Such an intuition supports our goal to derive a well-structured process model, because bonds of a process model that define concurrency must be synchronized in the same branch of the model where they forked.

**FIGURE 10.** Proper complete prefix unfolding of the system in Figure 6

Figure 10 shows a proper prefix of the system in Figure 6, which corresponds to the rigid component \( R_1 \) in Figure 1(a). Note that in our example, the proper prefix is different from the (non-proper) complete prefix unfolding of the system shown in Figure 7, and happens to be the unfolding of the system. This is not the general case; Figure 11 shows a complete prefix unfolding of the running example in [6] which is proper and smaller than the unfolding. Cutoff event \( e_4 \) in Figure 7 is not healthy as \( \text{Cut}(\{e_4\}) \setminus e_4 = \{e'_4\} \), while \( \text{Cut}(\{e_4\}) \setminus e_4 = \emptyset \), where \( e_4 \) is the corresponding event. The only cutoff event \( e'_4 \) in Figure 10 is healthy, this results in the proper prefix where all the concurrency introduced by event \( e_w \) is synchronized in the same branch of the prefix by event \( e'_4 \).

**FIGURE 11.** Proper complete prefix unfolding

A proper complete prefix unfolding of an acyclic system is clearly finite. For structuring purposes, when computing proper prefixes, we use an adequate order for safe systems proposed in [57]. This adequate order is a total order and results in minimal complete prefix unfoldings, if one only considers information about reachable markings induced by local configurations, which is the case for healthy cutoff events. Thus, the adequate order from [57] always yields minimal proper prefixes of safe acyclic systems, which applies to our case; recall that sound free-choice WF-nets are safe.

### 5.2. From unfoldings to graphs

The proper complete prefix unfolding of a process component \( R \) contains all ordering relations of all children of \( R \). For structuring, \( R \) is to be refined into a subtree among these ordering relations. The refinement requires this information to be preserved in a hierarchically decomposable form: an ordering relations graph.

**DEFINITION 5.2 (Ordering relations graph).** Let \( \beta = (N', \nu), N' = (B, E, G) \), be the proper prefix of a sound acyclic free-choice WF-system \( S = (N, M_1) \), \( N = (P, T, F, T, \lambda) \). Let \( x, y \in B \cup E \) be nodes of \( N' \).

- \( x \) and \( y \) are in proper causal relation, written \( x \leftrightarrow N' y \), iff \( (x, y) \in G^* \) or there exists a sequence \((e_1, \ldots, e_n)\) of healthy cutoff events of \( \beta \), \( e_i \in E \), \( 1 \leq i \leq n \), \( n \in N \), such that \( (x, e_1) \in G^* \), \( (\text{corr}(e_i), e_{i+1}) \in G^* \) for \( 1 \leq i < n \), and \( (\text{corr}(e_n), y) \in G^* \). \( x \) and \( y \) are in inverse proper causal relation, written \( y \leftrightarrow N' x \), iff \( x \leftrightarrow N' y \).

- Let \( R_{N'} = \{ \rightarrow_{N'}, \leftrightarrow_{N'}, \#_{N'}, \|_{N'} \} \) be the ordering relations of \( N' \). The proper conflict relation of \( N' \) is \( \boxtimes_{N'} = \#_{N'} \setminus \{ \rightarrow_{N'}, \leftrightarrow_{N'} \} \). The set \( R'_{N'} = \{ \rightarrow_{N'}, \leftrightarrow_{N'}, \boxtimes_{N'}, \|_{N'} \} \) forms the proper ordering relations of \( N' \).

- We refer to (proper) ordering relations \( R \) as observable, iff the relations in \( R \) only contain pairs of events that correspond to observable transitions.

- Let \( R_{N'} = \{ \rightarrow_{N'}, \leftrightarrow_{N'}, \boxtimes_{N'}, \|_{N'} \} \) be the observable proper ordering relations of \( N' \). An ordering relations graph \( G = (V, A, B, \sigma) \) of \( N' \) has vertices \( V \in E \) defined by events of \( \beta \) that correspond to observable transitions of \( N' \), arcs \( A = \rightarrow_{N'} \cup \boxtimes_{N'} \cup \|_{N'} \), and a labeling function \( \sigma : V \rightarrow B, B = T \setminus \{ \tau \} \) with \( \sigma(v) = \lambda(v) \), \( v \in V \).

Again, in the following we omit subscripts of ordering relations where the context is clear. An ordering relations graph of a proper complete prefix unfolding captures minimal and complete information about the ordering relations of events that correspond to observable transitions of the origination system. Figure 12(a) visualizes the ordering relations graph of the proper complete prefix unfolding in Figure 10.

In the figure, vertices represent events of the proper prefix, e.g., vertex \( a \) represents event \( e_a \). Due to a design decision, arcs of an ordering relations graph encode proper causal and proper conflict relations. The
The modular decomposition tree

The ordering relations graph not only encodes the ordering relations, it also inherits all information about well-structuredness from the proper prefix as pairing of gateways is preserved. The structuring technique in [6] proceeds by parsing the graph into a hierarchy of subgraphs that encode ordering relations of well-structured components. The thereby discovered hierarchy of subgraphs is then used to refine the origination of an rigid component into a subtree. As shown in [6], each subgraph corresponds to the notion of a module of the modular decomposition of a directed graph [61] – thus discovering well-structuredness in the relations of an unstructured process component.

Let $G = (V, A, B, \sigma)$ be an ordering relations graph. A module $M \subseteq V$ in $G$ is a non-empty subset of vertices of $G$ that are in uniform relation with vertices $V \setminus M$: if $v \in V \setminus M$, then $v$ has directed edges to all members of $M$ or to none of them, and all members of $M$ have directed edges to $v$ or none of them do. However, two vertices $v_1, v_2 \in V \setminus M$, $v_1 \neq v_2$, can have different relations to members of $M$. Moreover, the members of $M$ and $V \setminus M$ can have arbitrary relations to each other [61]. For example, $(d, e)$ is a module in Figure 12(a), as both $d$ and $e$ are in the inverse proper causal relation with $a$, and in proper conflict with every other vertex of the graph.

Two modules $M_1$ and $M_2$ of $G$ overlap, iff they intersect and neither is a subset of the other, i.e., $M_1 \setminus M_2$, $M_1 \cap M_2$, and $M_2 \setminus M_1$ are all non-empty. Module $M_1$ is strong, iff there exists no module $M_2$ of $G$, such that $M_1$ and $M_2$ overlap.

**Definition 5.3 (The modular decomposition tree).** The modular decomposition tree (MDT) of an ordering relations graph is the set of all its strong modules.

The modular decomposition substitutes each strong module of $G$ by a new vertex and proceeds recursively. The result is the MDT which is a unique canonical rooted tree. The MDT of a directed graph can be computed in linear time [61].

Now, a rigid process component $R$ of an RPST can be structured by refining $R$ in the RPST to a subtree $T_R$. The root of $T_R$ is child of $R$’s parent, each child of $R$ is attached to a leaf of $T_R$, the nodes of $T_R$ are defined by the modules of the MDT of $R$’s ordering relations graph. The class of a node of $T_R$ is determined by the characteristics of its defining MDT module. Every module of the MDT belongs to one out of four structural classes.

**Definition 5.4 (Module classes).**
Let $M$ be a module of an ordering relations graph $G$.

- $M$ is a trivial module, iff $M$ is singleton.
- $M$ is a linear module, iff there exists a linear order $(x_1, \ldots, x_{|M|})$ of elements of $M$, such that there is a directed edge from $x_i$ to $x_j$, iff $i < j$.
- $M$ is a complete module, iff the subgraph of $G$ induced by vertices in $M$ is either complete or edgeless. If the subgraph is complete, then we refer to $M$ as xor complete. If the subgraph is edgeless, then we refer to $M$ as and complete.
- $M$ is a primitive module, iff $M$ is neither trivial, nor complete, nor linear. A primitive module is concurrent, iff it contains a pair of vertices not connected by an edge in $G$.

**Figure 13.** Two different visualizations of the MDT of the ordering relations graph in Figure 12(a).

Figure 13(a) shows the MDT of the ordering relations graph in Figure 12(a). Besides the trivial modules, the MDT contains linear modules $L_1$, $L_2$, and $L_3$, xor complete module $C_1$, and and complete modules $C_2$ and $C_3$. Module $C_1$ is the root module, whereas trivial modules are leaves of the MDT. In the figure, each area enclosed by a dotted line defines a module composed of the modules inside the area. Edges between modules represent relations between every pair of vertices composed of one vertex from each of the adjacent modules. Module names hint at their class, e.g., $C_1$ is complete and $L_1$ is linear. Figure 13(b) shows an alternative visualization of the MDT given as
Algorithm 1: Structuring Acyclic Process Model

Input: An acyclic process model $P$  
Output: An equivalent structured process model 

1. Construct WF-net $N$ that corresponds to $P$  
2. Construct proper complete prefix unfolding $\beta$ of $N$  
3. Construct ordering relations graph $\mathcal{G}$ of $\beta$  
4. Compute $\mathcal{M}$ – the MDT of $\mathcal{G}$  

// Construct process model $P'$ by traversing $\mathcal{M}$ in postorder  

5. foreach module $m$ of $\mathcal{M}$ do  
6. switch class of $m$ do  
7. | case $m$ is trivial  
8. | Construct a task  
9. | case $m$ is and complete  
10. | Construct an and bond  
11. | case $m$ is xor complete  
12. | Construct a xor bond  
13. | case $m$ is linear  
14. | Construct a trivial or polygon  
15. | case $m$ is non-concurrent primitive  
16. | Construct a structured component using compiler techniques, e.g., [40]  
17. otherwise  
18. | FAIL  
19. return $P'$

A well-structured process model constructed in such a tree-like structure, where nodes represent non-trivial modules and edges encode containment relation.

An acyclic process model has an equivalent well-structured model, if its ordering relations graph contains no concurrent primitive module. According to [6], the behavior captured by other module classes can be expressed by well-structured process components. A trivial module corresponds to a task. A linear module corresponds to a polygon component. An and (xor) complete module corresponds to a bond with and (xor) gateways as entry and exit nodes. Finally, a primitive module without concurrency can be structured using standard compiler techniques [40]. A well-structured process model constructed in such a way is fully concurrent bisimilar with the original unstructured model.

Given all of the above, Algorithm 1 summarizes the structuring technique. Algorithm 1 traverses the MDT of an ordering relations graph of a rigid process component $P$ and constructs for each encountered module a process component from components that correspond to its child modules. The resulting hierarchy of components is the subtree that refines the rigid component $P$. In our example, the RPST of the process model in Figure 1(a) contains one rigid $R1$, see also Figure 8(a). $R1$ can be refined by a subtree of RPST nodes that correspond to modules of the MDT in Figure 13(b) to result in the RPST shown in Figure 8(b). First, modules $C2$ and $L3$ can be used to construct components $B2$ and $P4$ in Figure 1(b). Next, modules $L1$ and $C3$ must be employed to construct components $P2$ and $B3$. Then, module $L2$ results in component $P3$. Finally, module $C1$ results in component $B1$.

6. MAXIMALLY-STRUCTURED MODELS

In this section, we give a formal definition of the maximally-structured property of process models. Unlike well-structuredness, maximal structuredness is founded on a relation between the RPST and the MDT of the model. We gain insights into this relation by applying the structuring technique from Section 5 on the process model of Figure 2(a). To simplify language, in the following, we often skip several phases of the structuring technique when referring to the concepts of interest. For example, the “MDT of a process model” is the MDT obtained by mapping the model to a WF-net, constructing the proper prefix, then its ordering relations graph and, finally, computing the MDT of the ordering relations graph.

Figure 14 visualizes transformation steps 3–18 of Algorithm 1 applied on the process model of Figure 2(a). The proper prefix of the model (shown at the top of the figure) is the result of line 2 of the algorithm. Next (follow the arrow directions), the algorithm constructs the ordering relations graph and its MDT (lines 3–4). Finally, the algorithm attempts to construct a process model from the MDT (lines 5–18). As the
MDT contains primitive module \( P_2 \), the algorithm fails at line 18. However, the MDT exhibits some information on structuredness of the ordering relations: it contains linear module \( L_1 \) and \( xor \) complete module \( C_1 \). These modules can be used to construct structured components \( P_4 \) and \( B_1 \) shown at the bottom of Figure 14. If one is able to synthesize a process component which demonstrates the ordering relations captured in primitive module \( P_2 \), then one can construct a model which exhibits more structuredness than the original one. Note that in general a primitive module defines a subgraph of the ordering relations graph and, hence, the topology of the corresponding process component in the RPST cannot be deduced from the original model.

In a maximally-structured model every module of its MDT must have a corresponding component in its refined process structure tree.

**Definition 6.1** (Maximally-structured model). A process model is maximally-structured, iff there exists an isomorphism between the RPST and the MDT of the process model, where simple components of the RPST and trivial modules of the MDT are ignored, which assigns to every polygon component a linear module, to every bond a complete, to every rigid a primitive, and all primitives in the MDT are concurrent.

Recall that a simple component is either a trivial process component, or a polygon composed of two trivials (Section 4). Due to the properness of the complete prefix unfolding, the ordering relations graph of a given process model and, hence, its MDT are unique.

Consequently, each process model has exactly one unique fully concurrent bisimilar maximally-structured version.

**FIGURE 15.** (a) The RPST of the model in Figure 2(a), (b) the MDT and (c) the subtree of the RPST from the structuring scenario in Figure 14, all simplified

Figures 15(a) and 15(c) show the RPST of the model in Figure 2(a) and the subtree of the RPST from the structuring scenario in Figure 14, respectively, without simple components. In Figure 15(b), one can see the MDT from the structuring scenario in Figure 14, without trivial modules. This MDT is isomorphic to the RPST in Figure 15(c). Linear \( L_1 \) can be mapped to polygon \( P_4 \).

**FIGURE 16.** An extension of the structuring chain of Figure 9

Complete \( C_1 \) can be mapped to bond \( B_1 \). Primitive \( P_2 \) can be mapped to rigid \( R_2 \). In the final RPST of the maximally-structured version of Figure 2(a), polygon \( P_4 \) must be merged with polygon \( P_3 \) (as \( P_4 \) is a subsequence of \( P_3 \) and thus not canonical), see [58] for details. Note that Definition 6.1 is based on the implicit assumption that the isomorphism between both trees canonically extends to an isomorphism that maps process components with tasks onto modules of events with the same multisets of names/labels.

In the next section, we explain a technique for maximal structuring of process models, which essentially boils down to the technique for synthesis of a process component from a given ordering relations graph.

**7. MAXIMAL STRUCTURING**

The open problem from Section 5 is to structure a given rigid process component into an equivalent maximally-structured process component \( R \). In the light of Section 6, \( R \) has this property, iff (i) all primitive modules in the MDT of \( R \)’s ordering relations graph are concurrent, and (ii) there exists a bijection between non-singleton modules of the MDT and non-simple components of the RPST which assigns to each primitive module a rigid component, to each complete a bond, and to each linear a polygon. The maximal structuredness of \( R \) follows from the maximality of the modular decomposition: the ordering relations graph of \( R \) inherits all information about well-structuredness from the proper prefix of \( R \), and the MDT maximizes modules with a well-structured representation because of the decomposition into strong modules. If a concurrent primitive module \( M \) has well-structured child modules, then these modules are maximal again within \( M \). Only the relations within \( M \) have no structured representation as process model. That is, \( M \) is minimized by maximizing structuredness around and inside \( M \). This yields a technique for maximal structuring: one must be able to synthesize a process component that exhibits the ordering relations described in \( M \). Such a technique would allow to define unstructured process model topologies by mapping hierarchies of modules onto hierarchies of process components in Algorithm 1, e.g., the primitive module in Figure 14 onto the rigid component in Figure 2(b). The resulting process model would be maximally-structured.

In this section, we propose a solution to the synthesis problem, i.e., given an ordering relations graph (a module of an MDT) we synthesize a process model (a component of the RPST) that realizes the relations...
described in the graph. The central idea is to first construct from the ordering relations graph an occurrence net that is interpreted as the unfolding of the process model and that exhibits the same ordering relations. Refolding this unfolding then yields the process model we wish to synthesize. The entire procedure requires several phases that employ results of domain- and net theory [56], and on folding prefixes of systems [62]. The procedure extends the structuring approach of Figure 9 and is shown in Figure 16. The reconstruction of the occurrence net is explained in detail in Sections 7.1–7.3, and the refolding to a process model in Sections 7.4–7.6.

7.1. From graphs to partial orders

This section describes a translation from an ordering relations graph to a partial order of information. The partial order is an alternative formalization of the behavior captured in the graph. The elements of the partial order essentially correspond to the configurations of a branching process (Definition 3.11).

FIGURE 17. Ordering relations graph

The ordering relations graph in Figure 17 is a module from the running example of Section 6. The graph is a primitive module with all types of relations; f and f' represent events with the same label.

First, we give some definitions from the theory of partially ordered sets (posets) [56]. Let \((D,\preceq)\) be a poset. For a subset \(X\) of \(D\), an element \(y \in D\) is an upper (lower) bound of \(X\), iff \(x \leq y (x \geq y)\), for each element \(x \in X\). An element \(y \in D\) is a greatest (least) element, iff for each element \(x \in D\) holds \(x \leq y (x \geq y)\). An element \(y \in D\) is a maximal (minimal) element, iff there exist no element \(x \in D\) such that \(y \leq x (y \geq x)\); \(D_{\text{max}}\) and \(D_{\text{min}}\) denote the sets of maximal and minimal elements of \(D\). Two elements \(x\) and \(y\) in \(D\) are consistent, written \(x \uparrow y\), iff they have a joint upper bound, i.e., \(x \uparrow y \iff \exists z \in D : x \leq z \land y \leq z\); otherwise they are inconsistent. A subset \(X\) of \(D\) is pairwise consistent, written \(X\uparrow\), iff every two elements in \(X\) are consistent in \(D\), i.e., \(X\uparrow \iff \forall x,y \in X : x \uparrow y\). The poset \((D,\preceq)\) is coherent, iff each pairwise consistent subset \(X\) of \(D\) has a least upper bound (lub) \(\cup X\). An element \(x \in D\) is a complete prime, iff for each subset \(X\) of \(D\), which has a lub \(\cup X\), holds that \(x \leq \cup X \Rightarrow \exists y \in X : x \leq y\). Let \(P = (D,\preceq)\) be a poset. We write \(\mathcal{P}_P\) for the set of complete primes of \(P\). The poset \(P = (D,\preceq)\) is prime algebraic, iff \(\mathcal{P}_P\) is denumerable and every element in \(D\) is the lub of the complete primes it dominates, i.e., \(\forall x \in D : x = \cup \{y \mid y \in \mathcal{P}_P \land y \leq x\}\). A set \(S\) is denumerable, if it is empty or there exists an enumeration of \(S\) that is a surjective mapping from the set of positive integers onto \(S\). Figure 18 shows two prime-algebraic posets; their elements are sets (of events) ordered by set inclusion. The complete primes are written in bold face.

FIGURE 18. (a) Poset, and (b) augmented poset obtained from the graph in Figure 17

The behavior captured in an ordering relations graph can be translated to a prime algebraic partial order. Similar to [56], the elements of the partial order are the left-closed and conflict-free subsets of vertices of the graph. In our case the graph’s vertices represent events and each such set of events describes the history of events of some run of a system. Let \(\mathcal{G} = (V,A,B,\sigma)\) be a graph and let \(W\) be a subset of \(V\). \(W\) is conflict-free, iff \(\forall v_1,v_2 \in W : (v_1,v_2) \notin A \lor (v_2,v_1) \notin A\). \(W\) is left-closed, iff \(\forall v_1 \in W \forall v_2 \in V : (v_2,v_1) \in A \lor (v_1,v_2) \notin A\) \(\Rightarrow v_2 \in W\). We define \(\mathcal{L}[\mathcal{G}] = (H,\subseteq)\) as the partial order of left-closed and conflict-free subsets \(H\) of \(V\), ordered by inclusion \(\subseteq\). Figure 18(a) shows the poset \(\mathcal{L}\) of the graph in Figure 17. Theorem 7.1, inspired by Theorem 8 in [56], characterizes the posets \(\mathcal{L}[\mathcal{G}]\).

THEOREM 7.1. Let \(\mathcal{G} = (V,A,B,\sigma)\) be an ordering relations graph, let \(H \subseteq \mathcal{P}(V)\) be a set of left-closed and conflict-free subsets of \(V\), and let \(B = \{a \in A \mid a^{-1} \notin A\}\). Then, \(\mathcal{L}[\mathcal{G}] = (H,\subseteq)\) is a prime algebraic coherent partial order. Its complete primes are those elements of the form \([v]\ = \{v' \mid v',v \in W \land (v',v) \in B \land W^2\}\), with \(W \in H\).

Proof. Let \(X \subseteq H\) be pairwise consistent. Then, \(\cup X\) is conflict-free. \(\cup X = \cup X\) and, hence, \(\mathcal{L}[\mathcal{G}]\) is coherent. Each \([v]\, v \in V\), is clearly left-closed and conflict-free. Let \(X \subseteq H\) have lub \(\cup X\). \(X\) is pairwise consistent and \(\cup X = \cup X\). Each \([v]\) is a complete prime. If \([v]\ \subseteq \cup X\), then \(v \in \cup X\) and for some \(x \in X\) holds \(v \in x\) and, thus, \([v]\ \subseteq x\). It holds for each \(X \in H\) that \(X = \cup \{[v]\ \mid v \in \cup X\}\). Thus, each element of \(\mathcal{L}[\mathcal{G}]\) is a lub of the complete primes below it.

\(^{3}\mathcal{P}(V)\) denotes the set of all subsets of set \(V\), including the empty set and \(V\) itself.
Given an ordering relations graph, one can construct \( L[G] = (H, \leq) \) iteratively. Let \( h_1 \) and \( h_2 \) be subsets of \( V \), such that \( h_2 \not\subseteq h_1 = \{v\} \). Then \( h_1, h_2 \in H \), iff \( h_1 = \emptyset \) or \( \exists a \in h_1: (v, a) \notin A \), and \( \forall b \in h_1 : (b, v) \notin A \vee (v, b) \notin A \), and \( \forall c \in V \setminus h_1, (c, v) \in A. (v, c) \notin A \ \exists \ d \in h_1 : (c, d), (d, c) \in A \).

Finally, we augment \( L[G] = (H, \leq) \) with two fresh events \( i, o \notin V \) to ensure the existence of a single source \( i \) and sink \( o \) in the synthesis result. An augmented partial order of \( G \) is \( L^*[G] = (H^*, \leq) \), where \( H^* = \{\emptyset\} \cup \{h \cup \{i\} \mid h \in H\} \cup \{h \cup \{i, o\} \mid h \in H_{max}\} \).

Figure 18(b) shows \( L^*[G] \) of the graph in Figure 17. Adding new minimal and maximal elements \( i \) and \( o \) leaves the topology of the posets unchanged, so \( L^*[G] \) is a prime algebraic coherent poset.

**7.2. From partial orders to event structures**

The step from an ordering relations graph \( G \) to its augmented poset \( L^*[G] \) basically describes configurations of an unfolding that has the same ordering relations as \( G \). The complete primes of \( L^*[G] \) play a special role: they identify single events. Synthesizing the unfolding itself requires to define these events and their conflict relation explicitly. We do so by the help of the well-studied concept of an event structure [56].

**Definition 7.1 (Labeled event structure).**

An event structure is a triple \( E = (E, \leq, \oplus) \), where \( E \) is a set of events, \( \leq \) is a partial order over \( E \) called the causality relation, and \( \oplus \) is a symmetric and irreflexive relation in \( E \), called the conflict heredity, i.e., \( \forall e_1, e_2, e_3 \in E : e_1 \oplus e_2 \land e_2 \leq e_3 \Rightarrow e_1 \oplus e_3 \).

A labeled event structure \( E = (E, \leq, \oplus, \kappa) \) has a set \( C \) of labels, \( \tau \in C \), and \( \kappa : E \to C \) assigns to each event a label.

An ordering relations graph \( G \) differs from an event structure \( E \) in that \( G \) allows violations of conflict heredity. These violations, however, are not harmful; they express equivalent runs of a system. Note that posets computed in Section 7.1 capture all equivalent runs; these runs become explicit in event structures that will be computed in this section. Each prime algebraic coherent poset \( L^*[G] = (H, \leq) \) of an ordering relations graph \( G \) induces an event structure \( E[L^*[G]] \); each complete prime becomes an event, the ordering relation \( \leq \) induces the partial order \( \leq \) over events, conflicts arise between events that have no joint least upper bound in \( L^*[G] \).

The resulting event structure can intuitively be understood as an unfolding of the ordering relations graph that adheres to conflict heredity. The formal definition is an extension of [56, Definition 18]; it incorporates propagation of labels of an originate ordering relations graph to the corresponding event structure.

**Definition 7.2 (Event structure of partial order).**

Let \( G = (V, A, B, \sigma) \) be an ordering relations graph and let \( P = (H, \leq) \) be an augmented prime algebraic coherent partial order of \( G \). Then, \( E[P] \) is defined as the labeled event structure \( (E, \leq, \oplus, \kappa) \), where \( E = \mathcal{B}_P, \leq \) is \( \leq \) restricted to \( \mathcal{B}_P \), for all \( e_1, e_2 \in \mathcal{B}_P, e_1 \oplus e_2, \) if \( e_1 \) and \( e_2 \) are inconsistent in \( P \), and \( \mathcal{C} = \mathcal{B} \cup \{\tau\} \). Let \( e \in E \), and define \( \delta \) as \( \delta = \oplus e \cup \cup_{acc, at H} \). Then, \( \kappa(e) = \sigma(\delta) \), if \( \delta \in V \); otherwise \( \kappa(e) = \tau \), for all \( e \in E \).

Figure 19(a) visualizes \( E[L^*[G]] \) for the graph \( G \) of Figure 17. Events are complete primes of \( L^*[G] \) (see in boldface in Figure 18 and next to vertices in Figure 19). Directed edges encode causality (transitive dependencies are not shown), dotted edges represent implicit concurrency, whereas an absence of an edge hints at a conflict relation. The particular example of the event structure in Figure 19(a) is structurally similar to the graph in Figure 17: they differ only in Figure 19(a) having additional fresh \( i, o \) events. In general, event structures tend to have a different structure compared to the originate graphs. For instance, Figure 19(b) shows the event structure derived from the augmented poset of the graph in Figure 12(b).

**7.3. From event structures to occurrence nets**

The event structure \( E = (E, \leq, \oplus, \kappa) \) explicitly describes events of an unfolding that has the same ordering relations as the originate ordering relations graph \( G \). We obtain the unfolding by enriching \( E \) with conditions, that is, we translate \( E \) to an occurrence net. Nielsen et al. in [56] show a tight connection between event structures and occurrence nets. Let \( N = (B,E,G) \) be an occurrence net. Then, \( \xi[N] = (E*, G^* \cap E^2, \#_N \cap E^2) \) is a corresponding event structure. The next theorem, borrowed from [56], defines the converse: how to construct an occurrence net from a given event structure.

**Theorem 7.2.** Let \( E = (E, \leq, \oplus, \kappa) \), \( E \neq \emptyset \), be an event structure. Then, there exists an occurrence net \( \eta[E] \), such that \( E = \xi[\eta[E]] \).

**Proof.** Define the set \( CE = \{x \in E \mid \forall e_1, e_2 \in x : e_1 \neq e_2 \Rightarrow e_1 \neq e_2\} \). The events of \( \eta[E] \) are exactly those in \( CE \). The set of conditions is defined by \( B = \{(e, x) \mid e \in E, x \in CE, and \forall e' \in x : e \leq e' \} \cup \{(0, x) \mid x \in CE, and x \neq 0\} \). The flow relation is defined by \( G = \{(e, x), e' \} \mid (e, x) \in B, e' \in x) \cup \{(0, x), e' \} \mid (0, x) \in CE \). The set of conditions is defined by \( B = \{(e, x) \mid e \in E, x \in CE, and \forall e' \in x : e \leq e' \} \cup \{(0, x) \mid x \in CE, and x \neq 0\} \). The flow relation is defined by \( G = \{(e, x), e' \} \mid (e, x) \in B, e' \in x) \cup \{(0, x), e' \} \mid (0, x) \in CE \).
With Definition 7.3 we aim at preserving only essential behavior. Theorem 7.2 defines a "maximal" construction, see [47x607]B,e[47x215],i.e., the resulting nets tend to contain much redundancy.

In the following we consider labeled event structures and correspondingly labeled occurrence nets to describe system behavior where a transition may occur in several contexts, e.g., after a join. A labeled occurrence net generalizes the notion of a branching process of a (labeled) net system (Definition 3.9) as it describes system behavior when the system is not known – which is the case here, as we want to synthesize one.

A labeled occurrence net \( N = (B, E, G, T, \lambda) \) is an occurrence net \( (B, E, G) \) (Definition 3.8) where \( \lambda : B \cup E \to T, \tau \in T \), assigns each node \( x \in B \cup E \) a label \( \lambda(x) \).

Every branching process \( \beta = (N, \nu) \), \( N = (B, E, G) \) of a labeled net system \( S = (N_S, M_0) \), \( N_S = (P, T, F, T, \lambda) \) induces the labeled occurrence net \( (B, E, G, T, \nu \circ \lambda) \) that describes the ordering of occurrences of labels \( T \) instead of occurrences of transitions of \( S \).

Theorem 7.2 canonically lifts to labeled event structures and labeled occurrence nets: each labeled event structure \( E = (E, \leq, \varnothing, C, \kappa) \) induces the labeled occurrence net \( \eta[E] = (B, E, G, \mathcal{C} \cup \{ \tau \}, \kappa') \) which preserves the labels of events and assigns each condition label \( \tau \), i.e., for all \( e \in E, \kappa'(e) = \kappa(e) \), and for all \( b \in B, \kappa'(b) = \tau \).

Figure 20 shows the labeled occurrence net which is constructed from the event structure shown in Figure 19(a) using the principles of Theorem 7.2. Theorem 7.2 defines a "maximal" construction, see [56], i.e., the resulting nets tend to contain much redundancy. With Definition 7.3 we aim at preserving only essential behavioral dependencies.

**Definition 7.3 (Conditions).**

Let \( N = (B, E, G, T, \lambda) \) be a labeled occurrence net.

- A condition \( b \in B \) is redundant, if \( b = \varnothing \lor \exists b' \in B, b \neq b' : b' \in (\bullet b) \lor b = \varnothing \lor \exists b' \in B, b \neq b' : (b = b' \lor (b \neq \varnothing)) \).
- A condition \( b \in B \) is subsumed by condition \( b' \in B, b \neq b' \), if \( b = \bullet b' \lor b' \in b \).
- A condition \( b \in B \) denotes a transitive conflict between events \( e_1, e_2 \in E \), if \( \lambda(e_1) \neq \lambda(e_2) \) and there exists condition \( b' \in B, b \neq b' \), and events \( f_1, f_2 \in b' \), \( (f_1 \sim_N e_1) \land (f_2 \sim_N e_2 \lor f_2 = e_2) \).
- Any other condition is required.

A redundant condition has no pre-event (post-event), and is not a pre-condition (post-condition) of the initial (a final) event. A subsumed condition \( b \) always has a sibling \( b' \) expressing the same constraints for larger set of events. A condition \( b \) denotes a transitive conflict between two events, if an "earlier" condition \( b' \) already denotes this conflict. Subsumed conditions are shaded light-grey in Figure 20 and transitive conflicts dark-grey. All these conditions can be removed from the occurrence net without losing information about ordering of events.

An exception to transitive conflicts is a condition \( b \) shared by two post-events \( e_1, e_2 \) with the same label. Here, \( b \) not only expresses conflict, but also the only direct causal dependency of \( e_1 \) and \( e_2 \) on the pre-event of \( b \); such a condition is required (Definition 7.3).

For synthesizing a Petri net from the occurrence net obtained from an ordering relations graph, we remove from the occurrence net first all redundant conditions, then all subsumed conditions, and finally all transitive conflicts. Removing these conditions from the net in Figure 20 yields the net in Figure 23. Note that all conditions are labeled \( \tau \). Condition \( b_9 \) highlights the exception to transitive conflicts: it is the only condition expressing that \( f \) depends on \( c \) and, hence, must be part of the occurrence net. Also the resulting net still contains a number of implicit conditions, i.e., conditions which could be removed from the net without changing the ordering relations such as \( b_{11} \) denoting \( e_2 \rightarrow e_8 \) which is also expressed by the path \( e_2, b_9, e_8, b_{15}, e_8 \). We shall see that these remaining implicit conditions are vital for synthesizing a Petri net from a given occurrence net.

### 7.4. From occurrence nets to nets

**(the basic idea)**

The occurrence net obtained by Theorem 7.2 and after removing redundant, subsumed, and transitive conflict conditions (Definition 7.3) is already a process model – though one with duplicate structures and multiple sinks. We obtain a more compact model with a single sink by folding the occurrence net.

We first illustrate the idea on a simple, special case and then present the general approach. Consider the occurrence net \( N \) in Figure 21 which contains no implicit conditions. Intuitively, we obtain a process model from \( N \) by folding any two nodes of \( N \) which have isomorphic...
The algorithm for constructing a future equivalence is characterized co-inductively:

Two nodes of an occurrence net are future equivalent only if they have the same label and their post-sets are future equivalent.

The equivalence classes of the future equivalence define the nodes of the folded net: for each equivalence class, fold all its nodes into one node, preserving the arcs. The branching process of the folded net is exactly the original occurrence net, see [62, Theorem 8.7].

For the occurrence net $N$ in Figure 21 consider the future equivalence $\sim_f$ with the classes $\{b_{17}, b_{18}\}$, $\{e_8, e_9\}$, $\{b_{15}, b_{16}\}$, $\{b_{13}, b_{14}\}$, $\{e_6, e_7\}$, $\{b_9, b_{10}\}$, and all other nodes remaining singleton. Folding $N$ under $\sim_f$ yields the net in Figure 22 which has $N$ as its branching process.

The future equivalence captures the essence of our behavioral equivalence criterion for structuring, the fully concurrent bisimulation [6, Definition 12], in a stronger form that suits folding. Every future equivalence on an occurrence net $N$ yields a fully concurrent bisimulation relation on the partially ordered runs described by $N$. The converse does not hold as a future equivalence also considers invisible events of the net. Merging future equivalent events of $N$ into the same transition preserves the ordering relations encoded in $N$, see [62, Theorem 8.7] for the formal proof.

Folding an occurrence net $N$ also requires to correctly fold pre- and post-conditions of events while treating implicit conditions in the right way. Thereby, the event with the largest number of non-implicit pre-conditions in an equivalence class determines the number of predecessors for the entire class; all other events in the class “fill up” their pre-set with implicit conditions; correspondingly for post-sets. To formalize this, we need to introduce some notions.

For an occurrence net $N = (B, E, G, T, \lambda)$, let $\text{implicit}_N \subseteq B$ be the set of implicit conditions of $N$, i.e., $b \in \text{implicit}_N$ iff $(e_1) = b \ast \ast \ast (e_2)$ and there is a path from $e_1$ to $e_2$ in $N$ without $b$.

\[ 4 \text{Every prefix } \pi \text{ of a labeled occurrence net } N \text{ that contains no conflicting events is a partially ordered run [53].} \]
Let $\sim \subseteq (B \times B) \cup (E \times E)$ be an equivalence relation. For an equivalence class $(x)$ of $\sim$, let $\mathit{maxpre}(x)$ be the largest number of non-implicit predecessors of all members of $(x)$, i.e., $\mathit{maxpre}(x) = \{x' \mid x' \in (x) \text{ s.t. for all } x'' \in (x) \text{ holds } |x' \setminus \text{implicit}_N| \geq |x'' \setminus \text{implicit}_N|\}$; correspondingly let $\mathit{maxpost}(x)$ be the largest number of non-implicit successors of all members of $(x)$. For sets $X, Y \subseteq B$ we write $X \sim Y$ iff $X = \{x_1, \ldots, x_k\}, Y = \{y_1, \ldots, y_k\}$ and $x_i \sim y_i$, for all $1 \leq i \leq k$.

**Definition 7.5 (Folding equivalence).**

Let $N = (B, E, G, T, \lambda)$ be a labeled occurrence net, $\forall b \in B : \lambda(b) = \tau$. An equivalence relation $\sim \subseteq (B \times B) \cup (E \times E)$ preserves the environment of events iff for each equivalence class $(e)$ of $\sim$, $e \in E$, and for all $e_1, e_2 \in (e)$ holds:

- $3B_1 \subseteq e_1, B_2 \subseteq e_2 : B_1 \sim B_2 \land \forall i \in \{1, 2\} : |B_i| = \mathit{maxpre}(e_i) \land e_1 \setminus B_1 \subseteq \text{implicit}_N$.
- $3B_1 \subseteq e_1, B_2 \subseteq e_2 : B_1 \sim B_2 \land \forall i \in \{1, 2\} : |B_i| = \mathit{maxpost}(e_i) \land e_1 \setminus B_1 \subseteq \text{implicit}_N$.

An equivalence $\sim \subseteq (B \times B) \cup (E \times E)$ is a folding equivalence on $N$ iff $\sim$ is a future equivalence and preserves the environment of events.

Considering the occurrence net $N$ in Figure 23, the equivalence $\sim_f$ with the classes $\{b_{17}, b_{18}\} = \{e_8, e_9\}$, $\{b_{11}, b_{14}\}$, $\{b_{15}, b_{16}\}$, $\{e_6, e_7\}$, $\{b_6, b_{10}\}$, and all other nodes remaining singleton, is a folding equivalence on $N$. In particular, in the equivalence class $\{e_8, e_9\}$ the pre-set of event $e_9$ defines that all events have to have 2 pre-conditions that are mutually equivalent. Hence, $\{b_{15}, b_{16}\}$ and $\{b_{11}, b_{14}\}$ are equivalence classes of $\sim_f$ where the second class contains the implicit condition $b_{14}$. The remaining pre-conditions of $\{e_8, e_9\}$ need not be equivalent.

Without implicit conditions, folding would not succeed as it can be seen from the occurrence net in Figure 23 where implicit conditions are highlighted grey. The two equivalent events $e_8$ and $e_9$ differ in the number of non-implicit pre-conditions. To consistently fold $e_8$ and $e_9$ w.r.t. their pre- and post-sets, the pre-set of $e_9$ has to be extended with one implicit condition during folding.

We fold an occurrence net to a Petri net by merging all nodes of a folding equivalence class into the same node – except for equivalence classes consisting of implicit conditions only, these are discarded.

**Definition 7.6 (Folded net).**

Let $N = (B, E, G, T, \lambda)$ be a labeled occurrence net s.t. $\forall b \in B : \lambda(b) = \tau$. Let $\sim$ be a folding equivalence on $N$; write $(x)_f = \{y \mid y \sim_f x\}$ for the equivalence class of $x$. The folded net of $N$ under $\sim_f$ is the net $N_f = (B_f, E_f, G_f, T, \lambda_f)$ where

- $B_f = \{(b)_f \mid b \in B, b \notin \text{implicit}_N\}$,
- $E_f = \{(e)_f \mid e \in E\}$,
- $G_f = \{(x)_f, (y)_f \mid (x, y) \in G, (x)_f, (y)_f \in B_f \cup E_f\}$,
- $\lambda_f((x)_f) = \lambda(x)$.

Folding $N$ of Figure 23 under $\sim_f$ given above yields the net $N_f$ shown in Figure 24. Folding $N$ into $N_f$ preserves the behavior of $N$, see [62, Theorem 8.7].

![Figure 23](image_url)

**Figure 23.** Simplified occurrence net obtained from Figure 20

![Figure 24](image_url)

**Figure 24.** Folded net obtained from Figure 23

A simple algorithm to compute a folding equivalence traverses the given finite occurrence net backwards in a breadth-first manner. The conditions of the occurrence net without any post-event have equivalent futures. Correspondingly, their pre-events with the same label have equivalent futures. Building the folding equivalence backwards in this way ensures that only future equivalent events are put into the same equivalence class. Branching and backtracking are used whenever for a condition $b$ there are two or more pairwise concurrent conditions that could be folded with $b$. Each option is explored and the most-compact folding is chosen. For instance in Figure 21 after folding $b_{17} \sim_f b_{18}$ and $e_8 \sim_f e_9$, for $b_{15}$ the folding options $b_{14}$ and $b_{16}$ can be explored; backtracking yields $b_{16}$ as the better match for $b_{15}$ because of their $f$-labeled pre-events.

When extending the folding equivalence to pre-conditions of equivalent events $E'$, for instance for $E' = \{e_8, e_9\}$, implicit conditions are taken into account as follows:

- Pick the event $e \in E'$ with the largest set $B'$ of non-implicit pre-conditions, e.g., $\{b_{14}, b_{16}\} \subseteq e_9$.
- For each $b \in B'$, extend the folding equivalence with a non-implicit or implicit condition $b' \in e'$.
for all other events $e' \in E'$, preferring non-implicit conditions over implicit ones, e.g., $b_{16} \sim_f b_{15}$, $b_{14} \sim_f b_{11}$.

- Finally, remove all non-implicit conditions not required in this step, e.g., $b_5, b_6, b_{13}$.

The second step ensures that pre-sets of equivalent events are preserved, the third step ensures that post-sets of equivalent events (that are identified in subsequent steps) are preserved. Various heuristics improve exploration and backtracking when matching pre-conditions of events with each other. When the future equivalence cannot be extended further, the net can be folded according to Definition 7.6. Applying this procedure on our example yields the folded net shown in Figure 24 without the dashed conditions and arcs.

### 7.6. From nets to process models

The folding was the second to last step in synthesizing a process model from a given ordering relations graph. We obtained a Petri net $N_f$ which we now transform into a process model $P$ using the principles of Figure 5 in the reverse direction.

![Figure 25](image.png)

**FIGURE 25.** Process model obtained from Figure 24

The initial transition $i$ (final transition $o$) is mapped to the source (sink) node of $P$. Every other transition of $N_f$ becomes a task of $P$. Gateways of $P$ follow from non-singleton pre- and postsets of nodes of $N_f$. A transition $t$ with two or more pre-places is preceded by an and join; two or more post-places of $t$ define an and split; the pre- and post-sets of places define xor splits and joins, respectively; and gateways are always positioned closer to the task. In our example, $e_1 \bullet$ defines and split $s$ in Figure 25, $b_2 \bullet$ defines xor split $u$, $e_2 \bullet$ defines and split $v$, $e_6 \bullet$ defines and join $t$, and $b_0 \bullet$ defines xor join $j$ positioned between $t$ and $v$ (and gateways closer to tasks); correspondingly for all other gateways. The arc from $e_2$ to $(b_{11}, b_{14})$ which was obtained from a transitive conflict (Definition 7.3) results in an important control-flow arc from $w$ to $y$ without any task.

This concludes our technique for maximal structuring. Returning to our running example, we complete the maximal structuring of the model of Figure 2(a) by placing the synthesized process model $R_1$ of Figure 25 at the corresponding spot in the RPST of Figure 14(bottom). Recall that this RPST was obtained from the original process model using Algorithm 1. Placing $R_1$ at its designated spot yields the maximally-structured model of $P$ shown in Figure 2(b).

### 8. EVALUATION

The overall approach has been implemented in a tool, namely bpstruct, which is publicly available. Using bpstruct we conducted an evaluation to assess the performance of our techniques and to analyze the amount of duplication introduced during the structuring. All tests were performed on a laptop with a dual core Intel processor, 2.53 GHz, 4 GB of memory, running Microsoft Vista and SUN Java Virtual Machine version 1.6 (with 512 MB of allocated memory). To eliminate load time from the measures, each test was executed five times, and we recorded the average execution time of the second to fifth run. In the following, we provide details about the dataset used for the study and discuss the results of the experiments.

#### 8.1. Dataset

The study was conducted on a collection of process models extracted from industrial practice that has been publicly released for research purposes [63]. More precisely, we used the set of WF-nets provided in Woflan [64, 65] file format. In contrast to the original collection, where a large number of process models has multiple start nodes and/or multiple end nodes, the WF-nets have been completed such that each WF-net has a single source and a single sink place while preserving the original behavior. The reader is referred to [63] for a detailed description of the dataset and the underlying completion process.

In a first stage we removed all unsound WF-nets from the collection (approximately half of all nets). Every sound WF-net was parsed using the RPST decomposition as described in [66]. Every bond and polygon in the RPST was abstracted to a single transition. For each rigid component identified in the RPST a process model was synthesized using the approach described in Section 7.6. Two nodes were added to mark the entry and exit points, respectively. This procedure yielded a total of 170 sound unstructured process models. Among them, 115 are heterogeneous acyclic rigids (acyclic rigids with xor and and gateways), 39 are and rigids (acyclic rigids with and gateways only), 14 are cyclic rigids and 2 are xor rigids (rigids with xor gateways only). For the purpose of this study, we only kept models with heterogeneous acyclic rigids and and rigids (154 process models). To ease the analysis, we further classified the heterogeneous rigids into “structurable” and “maximally structurable”, accordingly. Table 2 summarizes the size of the models used for the study. In the table, and rigids are referred

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5http://code.google.com/p/bpstruct
6http://service-technology.org/soundness
to as inherently unstructured. The size of the models after structuring is shown in parenthesis. There were two exceptionally large process models in the dataset, one “structurable” and the other one “maximally structurable”. Both models have been excluded when calculating the average sizes. However, their sizes correspond to maximum values in their structural classes in Table 2.

8.2. Results

Our study reveals that out of the 154 process models, 110 models (71.43%) can be structured into well-structured models. More importantly, there exist models, in our case 5 (3.25%), which require the extension proposed in this article to achieve maximal-structuring, while 39 models (25.32%) are inherently unstructured. Concerning performance, Figure 26(a) presents the execution times relative to the number of events in the proper complete prefix unfolding, including a trend line for each structural class. It can be easily noted that the execution time is highly correlated to the size of the proper prefix. We observed a significant difference in the processing time for “maximally structurable” models compared to “structurable” models. Nevertheless, the average time for structuring was in the order of milliseconds, with a few exceptions. We found two exceptionally large cases: one model (“structurable”) with 119 nodes (the proper prefix had 2429 events) and the other one (“maximally structurable”) with 124 nodes (the proper prefix had 913 events), requiring 9 and 1 seconds for structuring, respectively.

Figure 26(b) presents the variation in the size of models, i.e., number of nodes, after structuring. On average, the model’s size decreased by about 15%, with a standard deviation of 0.817. This can be easily confirmed in the figure, as most of the points are located under the diagonal (which corresponds to a ratio 1:1), particularly in the case of “structurable” models. Recall that models were, in most of the cases, augmented with some additional elements (i.e., and gateways and transitive flow relations) to transform them into single exit models. Therefore, the reduction in size can be explained by the removal of gateways and transitive flow during the structuring performed by bpstruct. Conversely, the sizes of and rígids remained the same for this dataset. In additional internal experiments, we found that for certain and rígids it is also possible to observe a reduction on the size of the (maximally-)structured version when redundant elements are eliminated, e.g., spurious flow relations/gateways. The dataset used in our experiments is publicly available at bpstruct web site, including the graphical version of the process models in PDF file format.

9. CONCLUSION

In [6], we presented for the first time the full characterization of the class of acyclic process models that have an equivalent structured version along with a structuring method. The method stops when the input model contains an inherently unstructured process component. This article completes the approach by providing a method to synthesize the components corresponding to inherently unstructured parts of the input model.

Close to our setting, the problem of synthesizing nets from behavioral specifications has been a line of active research for about two decades [67, 68]. This area has given rise to a rich body of knowledge and to a number of tools, in particular petrify [67] and viptool [68]. Yet, these solutions fail in our setting: petrify aims at maximizing concurrency while our synthesis preserves

\(^7\)http://code.google.com/p/bpstruct/wiki/MaxStructEvaluation
given concurrency, \texttt{viptool} synthesizes nets with arc weights, which do not map to process models.

The approach is implemented in a tool, namely \texttt{bpstruct}, which is publicly available. The running time of our structuring technique is dominated by the time required to compute proper prefixes of safe systems, which has an upper bound of $O(|T| \cdot R^\xi)$, see [57], where $T$ is the set of transitions, $R$ is the number of reachable markings, and $\xi$ is the maximal size of the presets or postsets of the transitions in the origination system. Concerning the extension for maximal structuring, the theoretic discussion in this article implies exponential time and space complexities when constructing posets (this is due to our intent to stay close to the existing theory). However, in practice, given an ordering relations graph one can construct a poset which only contains information from the graph, without introducing duplicate events, and thus stay linear to the size of the graph. At the theoretical level this requires introduction of a concept of a cutoff for posets followed by an adjustment of the theories along subsequent transformation steps. The folding step reverses the unfolding and, thus, in the best case can be performed in the same time. All other structuring steps have linear or low polynomial time complexities. Evaluations we have conducted with sample process models show that the worst case complexity for constructing proper prefixes is a rare obstacle when structuring. This finding confirms the results of other works that have empirically shown that complete prefix unfolding computation is efficient in practice, see e.g., [57]. However, we also see a potential for improving the theoretical upper bound for the running time of our structuring technique. This can be achieved in future works by specifying the time complexity of an algorithm for constructing complete prefix unfoldings of free-choice systems.

The fact that the running time of structuring depends on the size of the result, allows to introduce heuristics to terminate computation when the result gets large, e.g., when the event duplication factor is larger than two. Moreover, we envision a technique which can decide on-line, i.e., during the construction of the proper prefix, that from now on the prefix defines an ordering relations graph which contains a primitive module and, thus, the model cannot be structured. However, in practice we have never observed such a need with our implementation in most cases delivering results in milliseconds. Note that the amount of task duplication for the running time of our structuring technique can be suppressed in the preprocessing step by unfolding and then refolding the model, by following the principles described in Sections 5 and 7. The refolded model is (in some sense) in a canonical form and should be employed for structuring. Note that the resulting refolded model is sometimes well-structured. The detailed analysis of such a preprocessing step is left for future work.

Our ongoing work aims at extending the method to handle models with loops. In our initial investigations, we try to derive a condition for unfolding truncation which results in prefixes with sufficient information to recognize all SESE loop components hidden within process models. The first results show that such a condition must be evaluated iteratively as complex overlapping loop topologies keep unfolding.

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REFERENCES


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