On the verification of interorganizational workflows

Citation for published version (APA):

Document status and date:
Published: 01/01/1997

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
On the verification of Interorganizational Workflows

by

W.M.P. van der Aalst

ISSN 0926-4515

All rights reserved
editors: prof.dr. R.C. Backhouse
         prof.dr. J.C.M. Baeten

Reports are available at:
http://www.win.tue.nl/win/cs

Computing Science Reports 97/16
Eindhoven, November 1997
On the Verification of Interorganizational Workflows

W.M.P. van der Aalst
Department of Mathematics and Computing Science, Eindhoven University of Technology,
P.O. Box 513, NL-5600 MB, Eindhoven, The Netherlands, telephone: +31 40 2474295,
fax: +31 40 2463992, e-mail: wsinwa@win.tue.nl

To date, workflow management focuses on improving the effectiveness and efficiency of business processes within one organization. However, today's corporations are challenged to cross organizational boundaries. Phenomena such as electronic commerce, extended enterprises and the Internet stimulate the cooperation between organizations. Therefore, it is interesting to consider workflows distributed over a number of organizations. Interorganizational workflow offers companies the opportunity to re-shape business processes beyond the boundaries of individual organizations. In this paper, we use message sequence charts to specify the interaction between organizations. Petri nets are used to model interorganizational workflows. Two important questions are answered by the results presented in this paper: (1) What are the minimal requirements any interorganizational workflow should satisfy?, and (2) How to decide whether an interorganizational workflow (modeled in terms of Petri nets) is consistent with the interaction structure specified in terms of a message sequence chart?

Keywords: interorganizational workflow; Petri nets; message sequence charts; workflow management; electronic commerce, analysis of workflows.

1 Introduction

Workflow management promises a new solution to an age-old problem: controlling, monitoring, optimizing and supporting business processes. What is new about workflow management is the explicit representation of the business process logic which allows for computerized support. At the moment, there are more than 200 workflow products commercially available and many organizations are introducing workflow technology to support their business processes. Clearly, workflow management is becoming a mature technology which can be applied within organizations. However, the number of business processes where multiple organizations are involved is increasing rapidly. Technologies such as Electronic Data Interchange (EDI), the Internet, and the World Wide Web (WWW) enable multiple organizations to participate in shared business processes. The rise of electronic commerce, virtual organizations and extended enterprises highlights the fact that more and more business processes are crossing organizational boundaries ([19]). This means that workflow management should be able to deal with workflow processes which
span across multiple organizations.

This paper focuses on interorganizational workflows, i.e., several business partners are involved in shared workflow processes. In this paper, we restrict ourselves to structured processes with a predefined set of tasks and routing constructs. In many cases, where the coordination structure and the interaction between the business partners is not specified explicitly, this is not a realistic assumption ([23]). Nevertheless, there are numerous situations where the organizations participating in a shared workflow processes feel the need to specify the coordination structure explicitly.

There are several mechanisms to enable interorganizational workflow:

- capacity sharing: tasks are executed by external resources under the control of one workflow manager,
- chained execution: the process is divided into subsequent phases and each business partner takes care of one phase,
- subcontracting: a subprocess is executed by another organization,
- case transfer: each partner uses the same workflow process and cases are transferred from one partner to another partner,
- loosely coupled: each partner takes care of a specified part of the workflow process.

This paper focuses on loosely coupled workflow processes. Each business partner has a private workflow process which is connected to the workflow processes of some of the other partners. Two communication mechanisms are used to interact: (i) asynchronous communication and (ii) synchronous communication. In this paper, Message Sequence Charts (MSC) (cf. [8, 18, 22, 26, 15]) are used to specify the communications between business partners.

Loosely coupled workflow processes operate essentially independently, but have to synchronize at certain points to ensure the correct execution of the overall business process. Synchronization of parallel processes is known to be potential source of errors (e.g. deadlock and livelocks). Therefore, it is difficult to establish the correctness for complex interorganizational workflows. This paper introduces a notion of correctness which should be satisfied by any interorganizational workflow. Based on this notion, we also present an analysis technique to verify the correctness of an interorganizational workflow. Moreover, we show how to check whether the interorganizational workflow is consistent with respect to the communication structure (i.e. the protocol) specified in terms of message sequence charts.

Because processes are a dominant factor in workflow management, it is important to use an established framework for modeling and analyzing workflow processes [17, 20, 21]. In this paper, we use a framework based on Petri nets. Petri nets are a well-founded process
modeling technique. The classical Petri net was invented by Carl Adam Petri in the sixties. Since then Petri nets have been used to model and analyze all kinds of processes with applications ranging from protocols, hardware, and embedded systems to flexible manufacturing systems, user interaction, and business processes. There are several reasons for using Petri nets for workflow modeling: their formal semantics, graphical nature, expressiveness, analysis techniques and tools provide a framework for modeling and analyzing workflow processes ([3, 5, 11, 12, 24, 28]).

In the remainder of this paper we will show how Petri nets can be applied to the domain of interorganizational workflows. We will show that the correctness of interorganizational workflows can be verified using standard Petri net techniques. We will also show how to check whether the communication structure between loosely coupled workflow processes is consistent respect to the communication structure specified in terms of message sequence charts. We will show that consistency coincides with the presence of so-called implicit places. However, we first introduce some Petri-net terminology and some results for the analysis of a single workflow within an organization.

2 Petri nets

This section introduces the basic Petri net terminology and notations. Readers familiar with Petri nets can skip this section. For a review of the history of Petri nets and an extensive bibliography the reader is referred to Murata [25].

The classical Petri net is a directed bipartite graph with two node types called places and transitions. The nodes are connected via directed arcs. Connections between two nodes of the same type are not allowed. Places are represented by circles and transitions by rectangles.

Definition 1 (Petri net) A Petri net is a triple \((P, T, F)\):

- \(P\) is a finite set of places,
- \(T\) is a finite set of transitions \((P \cap T = \emptyset)\),
- \(F \subseteq (P \times T) \cup (T \times P)\) is a set of arcs (flow relation)

A place \(p\) is called an input place of a transition \(t\) iff there exists a directed arc from \(p\) to \(t\). Place \(p\) is called an output place of transition \(t\) iff there exists a directed arc from \(t\) to \(p\).

We use \(\bullet t\) to denote the set of input places for a transition \(t\). The notations \(t\bullet, \bullet p\) and \(p\bullet\) have similar meanings, e.g. \(p\bullet\) is the set of transitions sharing \(p\) as an input place. Note that we restrict ourselves to arcs with weight 1. In the context of workflow procedures it makes no sense to have other weights, because places correspond to conditions.

At any time a place contains zero or more tokens, drawn as black dots. The state \(M\), often referred to as marking, is the distribution of tokens over places, i.e., \(M \in P \rightarrow N\). We will represent a state as follows: \(1p_1 + 2p_2 + 1p_3 + 0p_4\) is the state with one token in place
two tokens in $p_2$, one token in $p_3$ and no tokens in $p_4$. We can also represent this state as follows: $p_1 + 2p_2 + p_3$. To compare states, we define a partial ordering. For any two states $M_1$ and $M_2$, $M_1 \leq M_2$ iff for all $p \in P$: $M_1(p) \leq M_2(p)$.

The number of tokens may change during the execution of the net. Transitions are the active components in a Petri net: they change the state of the net according to the following firing rule:

1. A transition $t$ is said to be enabled iff each input place $p$ of $t$ contains at least one token.

2. An enabled transition may fire. If transition $t$ fires, then $t$ consumes one token from each input place $p$ of $t$ and produces one token for each output place $p$ of $t$.

Given a Petri net $PN = (P, T, F)$ and a state $M_1$, we have the following notations:

- $M_1[t]_{PN} M_2$: transition $t$ is enabled in state $M_1$ and firing $t$ in $M_1$ results in state $M_2$
- $M_1[\cdot]_{PN} M_2$: there is a transition $t$ such that $M_1[t]_{PN} M_2$
- $M_1[\sigma]_{PN} M_n$: the firing sequence $\sigma = t_1t_2t_3 \ldots t_{n-1} \in T^*$ leads from state $M_1$ to state $M_n$, i.e., $M_1[t_1]_{PN} M_2[t_2]_{PN} \ldots [t_{n-1}]_{PN} M_n$

A state $M_n$ is called reachable from $M_1$ (notation $M_1[*] M_n$) iff there is a firing sequence $\sigma = t_1t_2 \ldots t_{n-1}$ such that $M_1[t_1] M_2[t_2] \ldots [t_{n-1}] M_n$. The subscript $_{PN}$ is omitted if it is clear which Petri net is considered. Note that the empty firing sequence is also allowed, i.e., $M_1[*] M_1$.

We use $(PN, M)$ to denote a Petri net $PN$ with an initial state $M$. A state $M'$ is a reachable state of $(PN, M)$ iff $M[*] M'$. Let us define some properties of Petri nets.

**Definition 2 (Live)** A Petri net $(PN, M)$ is live iff, for every reachable state $M'$ and every transition $t$ there is a state $M''$ reachable from $M'$ which enables $t$.

**Definition 3 (Bounded, safe)** A Petri net $(PN, M)$ is bounded iff, for every reachable state and every place $p$ the number of tokens in $p$ is bounded. The net is safe iff for each place the maximum number of tokens does not exceed 1.

**Definition 4 (Strongly connected)** A Petri net is strongly connected iff, for every pair of nodes (i.e. places and transitions) $x$ and $y$, there is a path leading from $x$ to $y$.

### 3 WF-nets

Before we discuss the application of Petri nets to interorganizational workflow, we consider the modelling and analysis of workflows within one organization. In this paper, we focus on the 'process aspect' of workflow management, i.e. we abstract from data, resources and external triggers.
Workflows are case-based, i.e., every piece of work is executed for a specific case. Examples of cases are a mortgage, an insurance claim, a tax declaration, an order, or a request for information. Cases are often generated by an external customer. However, it is also possible that a case is generated by another department within the same organization (internal customer). The goal of workflow management is to handle cases as efficient and effective as possible. A workflow process is designed to handle similar cases. Cases are handled by executing tasks in a specific order. The workflow process definition specifies which tasks need to be executed and in what order. Alternative terms for workflow process definition are: ‘procedure’, ‘flow diagram’ and ‘routing definition’. In the workflow process definition, building blocks such as the AND-split, AND-join, OR-split and OR-join are used to model sequential, conditional, parallel and iterative routing (WFMC [27]). Clearly, a Petri net can be used to specify the routing of cases. Tasks are modeled by transitions and causal dependencies are modeled by places. In fact, a place corresponds to a condition which can be used as pre- and/or post-conditions for tasks. An AND-split corresponds to a transition with two or more output places, and an AND-join corresponds to a transition with two or more input places. OR-splits/OR-joins correspond to places with multiple outgoing/ingoing arcs. Moreover, in [I, 3] it is shown that the Petri net approach also allows for useful routing constructs absent in many workflow management systems.

A Petri net which models the process aspect of a workflow, is called a WorkFlow net (WF-net). It should be noted that a WF-net specifies the dynamic behavior of a single case in isolation.

Definition 5 (WF-net) A Petri net $PN = (P, T, F)$ is a WF-net (Workflow net) if and only if:

(i) $PN$ has two special places: $i$ and $o$. Place $i$ is a source place: $\bullet i = 0$. Place $o$ is a sink place: $o\bullet = 0$.

(ii) If we add a transition $t^*$ to $PN$ which connects place $o$ with $i$ (i.e. $\bullet t^* = \{o\}$ and $t^*\bullet = \{i\}$), then the resulting Petri net is strongly connected.

A WF-net has one input place ($i$) and one output place ($o$) because any case handled by the procedure represented by the WF-net is created if it enters the workflow management system and is deleted once it is completely handled by the workflow management system, i.e., the WF-net specifies the life-cycle of a case. The second requirement in Definition 5 (the Petri net extended with $t^*$ should be strongly connected) states that for each transition $t$ (place $p$) there should be a path from place $i$ to $o$ via $t$ ($p$). This requirement has been added to avoid ‘dangling tasks and/or conditions’, i.e., tasks and conditions which do not contribute to the processing of cases.

Figure 1 shows a WF-net. This WF-net models a workflow process composed of eight tasks: $t1, ..., t8$. The execution of task $t1$ enables two parallel flows: (i) $t3$ and $t2$ can be executed multiple times (iteration) followed by $t6$, and (ii) $t4$ or $t5$ followed by $t7$. The two parallel flows are synchronized by task $t8$. Note that sequential, conditional, parallel and iterative routing are present in this example.
4 Verification of WF-nets

The two requirements stated in Definition 5 can be verified statically, i.e., they only relate to the structure of the Petri net. However, there is an additional requirement which should be satisfied:

For any case, the procedure will terminate eventually and the moment the procedure terminates there is a token in place $o$ and all the other places are empty.

Moreover, there should be no dead tasks, i.e., it should be possible to execute an arbitrary task by following the appropriate route though the WF-net. These two additional constraints correspond to the so-called soundness property.

**Definition 6 (Sound)** A procedure modeled by a WF-net $PN = (P, T, F)$ is sound if and only if:

(i) For every state $M$ reachable from state $i$, there exists a firing sequence leading from state $M$ to state $o$. Formally:\footnote{Note that there is an overloading of notation: the symbol $i$ is used to denote both the place $i$ and the state with only one token in place $i$ (see Section 2).}

\[ \forall_M(i[*]M) \Rightarrow (M[*]o) \]
(ii) State \( o \) is the only state reachable from state \( i \) with at least one token in place \( o \). Formally:
\[
\forall_M (i[*]M \land M \geq o) \Rightarrow (M = o)
\]

(iii) There are no dead transitions in \((PN, i)\). Formally:
\[
\forall_{i \in T} \exists_{M, M'} i[*]M[i]M'
\]

Note that the soundness property relates to the dynamics of a WF-net. The first requirement in Definition 6 states that starting from the initial state \((state \ i)\), it is always possible to reach the state with one token in place \( o \) \((state \ o)\). If we assume fairness, then the first requirement implies that eventually state \( o \) will be reached. The fairness assumption is reasonable in the context of workflow management; all choices are made (implicitly or explicitly) by applications, humans or external actors. Clearly, they should not introduce an infinite loop. The second requirement states that the moment a token is put in place \( o \), all the other places should be empty. Sometimes the term proper termination is used to describe the first two requirements [14]. The last requirement states that there are no dead transitions (tasks) in the initial state \( i \).

Given WF-net \( PN = (P, T, F) \), we want to decide whether \( PN \) is sound. For this purpose we define an extended net \( \overline{PN} = (\overline{P}, \overline{T}, \overline{F}) \). \( PN \) is the Petri net that we obtain by adding an extra transition \( t^* \) which connects \( o \) and \( i \). The extended Petri net \( \overline{PN} = (\overline{P}, \overline{T}, \overline{F}) \) is defined as follows: \( \overline{P} = P, \overline{T} = T \cup \{t^*\}, \) and \( \overline{F} = F \cup \{(o, t^*), (t^*, i)\} \). Figure 2 illustrates the relation between \( PN \) and \( \overline{PN} \). The extended net \( \overline{PN} \) can be used to facilitate the verification of the soundness property. The following theorem shows that the extended net allows for the formulation of the soundness property in terms of well-known Petri net properties.

![Figure 2](image-url)

Figure 2: Given a WF-net \( PN \), we construct an extended net \( \overline{PN} = (P, T \cup \{t^*\}, F \cup \{(o, t^*), (t^*, i)\}) \).

**Theorem 1** A WF-net \( PN \) is sound if and only if \((\overline{PN}, i)\) is live and bounded.

**Proof.**
See [4] or [2].

Perhaps surprisingly, the verification of the soundness property boils down to checking whether the extended Petri net is live and bounded! This means that we can use standard Petri-net-based analysis tools to decide soundness.
5 Interorganizational workflows

In the previous two sections, we applied Petri nets to the modeling and analysis of workflows within one organization. Now it is time to consider interorganizational workflows. An interorganizational workflow is essentially a set of loosely coupled workflow processes. Typically, there are \( n \) business partners which are involved in one ‘global’ workflow process. Each of the partners has its own ‘local’ workflow process. Each local workflow process is private, i.e. the corresponding business partner has full control over the local part of the workflow. However, these local workflow processes need to communicate because they depend on each other for the correct execution of cases. The global workflow process consists of local workflow processes and an interaction structure. There are two ways to interact: asynchronous communication and synchronous communication. Asynchronous communication corresponds to the exchange of messages between local workflow processes. Synchronous communication forces local workflow processes to execute specific tasks at the same time.

Figure 3: An interorganizational workflow composed of two local workflows.

Figure 3 shows an interorganizational workflow which consists of two local workflows \( LWF_1 \) and \( LWF_2 \). There are three asynchronous communication elements: \( ac_1 \), \( ac_2 \), and \( ac_3 \). There is one synchronous communication element: \( sc_1 \). The asynchronous communication elements are also called communication places. These communication places are used to model causal dependencies, e.g., task \( t11 \) in \( LWF_2 \) has to wait for the completion
of task \( t1 \) in \( LWF1 \). The synchronous communication element \( sc1 \) forces the transitions \( t7 \) and \( t14 \) to be executed at the same time. Synchronous communication corresponds to the melting of a number of transitions, therefore we also use the term fusion set to denote a synchronous communication element. Definition 7 formalizes the concept of an interorganizational workflow.

**Definition 7 (IOWF)** An Interorganizational Workflow (IOWF) is a tuple

\[
IOWF = (PN_1, PN_2, \ldots, PN_n, P_{AC}, AC, T_{SC}, SC)
\]

where:

(i) \( n \in \mathbb{N} \) is the number of local workflow nets,

(ii) for each \( k \in \{1, \ldots, n\} \): \( PN_k \) is a WF-net with source place \( i_k \) and sink place \( o_k \),

(iii) for all \( k, l \in \{1, \ldots, n\} \): if \( k \neq l \), then \( (P_k \cup T_k) \cap (P_l \cup T_l) = \emptyset \),

(iv) \( T^\square = \bigcup_{k \in \{1, \ldots, n\}} T_k \), \( P^\square = \bigcup_{k \in \{1, \ldots, n\}} P_k \), \( F^\square = \bigcup_{k \in \{1, \ldots, n\}} F_k \),

(v) \( P_{AC} \) is the set of asynchronous communication elements (communication places),

(vi) \( T_{SC} \) is the set of synchronous communication elements (fusion sets),

(vii) \( P_{AC} \cap T_{SC} = \emptyset \), \( (P_{AC} \cup T_{SC}) \cap (P^\square \cup T^\square) = \emptyset \),

(viii) \( AC \subseteq P_{AC} \times \mathcal{P}(T^\square) \times \mathcal{P}(T^\square) \) is the asynchronous communication relation,

(ix) \( SC \subseteq T_{SC} \times \mathcal{P}(T^\square) \) is the synchronous communication relation,

(x) for all \( (t_1, x_1), (t_2, x_2) \in SC \): if \( t_1 \neq t_2 \), then \( x_1 \cap x_2 = \emptyset \).

Each asynchronous communication element corresponds to a place name in \( P_{AC} \). The relation \( AC \) specifies a set of input transitions and a set of output transitions for each asynchronous communication element. Each synchronous communication element is represented by a transition name in \( T_{SC} \) which corresponds to a set of fused transitions. The relation \( SC \) specifies for each element in \( T_{SC} \) the corresponding set of fused transitions. Requirement (x) states that these sets should be disjunct. Note that Definition 7 allows for communication elements which connect transitions within the same local workflow net. Although it does not make sense to do this, there is no compelling reason to forbid this kind of communication. Also note that each local workflow net has an input place \( i_k \) and an output place \( o_k \). Sometimes there is no need for these places, e.g., if one organization is a subcontractor of another organization, then the workflow of the subcontractor may be initiated by a message (i.e. an asynchronous communication element). However, for semantical reasons we add the input place \( i_k \) and an output place \( o_k \). Consider for example Figure 3; \( i2 \) and \( o2 \) can be removed without changing the actual behavior.

\[\mathcal{P}(T^\square) \text{ is the set of all non-empty subsets of } T^\square.\]
6 Verification of interorganizational workflows

In Section 4 we introduced a technique to verify the correctness of one workflow process definition in isolation. We can use this technique to prove that both local workflows in Figure 3 are correct, i.e., LWF1 and LWF2 are sound. However, an interorganizational workflow which is composed of a number of sound local workflows may be subject to synchronization errors. Consider for example the interorganizational workflow shown in Figure 3. It is possible that LWF1 executes t4 and LWF2 executes t12. In this case, the message in a2 is not handled properly. It is also possible that deadlocks are introduced by the communication elements. If t7 and t12 are fused by a synchronous communication element, the workflow will not be able to terminate if t13 is executed. Because of these problems, we are interested in a notion of soundness for interorganizational workflows. To define a global notion of soundness, we define the unfolding of an interorganizational workflow into a WF-net.

**Definition 8** Let IOWF = (PN1, PN2, ..., PNn, PAC, AC, TSC, SC) be an interorganizational workflow. U(IOWF) = (PU, TU, FU) is the unfolding of IOWF which is defined as follows:

(i) PU = P ⊇ AC ∪ {i, o},

(ii) TU = r(T ⊇ ) ∪ TSC ∪ {t, t0},

(iii) {i, o, t, t0} ∩ (P ⊇ ∪ T ⊇ ∪ AC ∪ TSC) = ∅,

(iv) r is a renaming function: r(x) = tSC if there is a tSC ∈ TSC and a y ∈ T ⊇ such that (tSC, y) ∈ SC and x ∈ y, otherwise r(x) = x,

(v) F' = F ⊇ ∪ {(t, p) ∈ T ⊇ ∩ P ⊇ | (p, x, y) ∈ AC ∧ t ∈ x} ∪

{(p, t) ∈ P ⊇ × T ⊇ | (p, x, y) ∈ AC ∧ t ∈ y} ∪

{(t, t0) | t ∈ [1, ..., n]} ∪ {(t0, t0) | k ∈ [1, ..., n]}

(vi) FU = {(r(x), r(y)) | (x, y) ∈ F'}.

In the unfolded net all the local WF-nets are connected to each other by a start transition t and a termination transition t0. Moreover, a global source place i and a global sink place o have been added. Asynchronous communication elements are mapped onto ordinary places (PAC). Transitions which are fused together by synchronous communication elements are replaced by new transitions (TSC). Note that we use a renaming function r to map old transitions onto new transitions. The result of the unfolding is a new WF-net.

**Lemma 1** Let IOWF = (PN1, PN2, ..., PNn, PAC, AC, TSC, SC) be an IOWF. U(IOWF) = (PU, TU, FU) is a WF-net.

**Proof.**
It is easy to see that the two requirements stated in Definition 5 are satisfied: (i) there is one source place i and one sink place o, and (ii) every node is on a path from i to o. □
It is easy to see that the behavior of the unfolded net corresponds to the overall behavior of the interorganizational workflow. This allows us to define the soundness property for interorganizational workflows.

**Definition 9 (Soundness)** An interorganizational workflow $IOWF$ is sound iff it is locally sound and globally sound. $IOWF$ is locally sound iff each of its local workflow nets $PN_k$ is sound. $IOWF$ is globally sound iff $U(IOWF)$ is sound.

The interorganizational workflow shown in Figure 3 is an example of workflow which is locally sound but not globally sound. The unfolded net is not sound, because if $t4$ and $t12$ fire, a token gets stuck in place $ac2$. The error can be corrected by replacing the asynchronous communication element $ac2$ by a synchronous communication element. Figure 4 shows an example of an interorganizational workflow which is globally sound but not locally sound. The WF-net $LWF2$ is not sound because an arbitrary number of tokens may get trapped in place $p14$. However, asynchronous communication element $ac2$ prevents this from happening in the unfolded net. These examples show that it is possible to have a locally sound interorganizational workflow which is not globally sound and vice-versa. In order to be truly sound, the interorganizational workflow should be both locally sound and globally sound. Figure 5 is an example of a sound interorganizational workflow.

The soundness of an interorganizational workflow $IOWF = (PN_1, ..., PN_n, P_{AC}, AC,$
Figure 5: A sound interorganizational workflow.

$T_{SC}, SC$ corresponds to the soundness of $n + 1$ WF-nets: $PN_1, \ldots, PN_n$ and $U(IOWF)$. Therefore, we can use Theorem 1 to verify the correctness of interorganizational workflows. This means that we can use standard techniques and software tools. For example, we can use Woflan ([16]). Woflan is an analysis tool dedicated to the analysis of workflows which are specified in terms of Petri nets.

For arbitrary interorganizational workflows, the soundness property is decidable but also EXPSPACE-hard ([2]). However, there are some interesting subclasses which allow for more efficient analysis techniques. For example, many workflow management systems only allow for workflow process definitions which correspond to free-choice Petri nets ([10]). For this subclass and several others (cf. [2]), the soundness property can be verified in polynomial time.

7 Message sequence charts

Interorganizational workflows are described in terms of individual tasks and causal relations. In most cases, the design of an interorganizational workflow starts with the specification of the communication structure, i.e., the protocol. Clearly, a description in terms of a Petri net is too detailed to start with. Therefore, another technique is needed to specify the communication structure between multiple loosely coupled workflows. In this paper,
we use Message Sequence Charts (MSC) extended with synchronous communication for this purpose.

Message sequence charts are a widespread graphical language for the visualization of communications between systems/processes [8, 22, 26]. The representation of message sequence charts is intuitive and focuses on the messages between communication entities. Figure 6 shows a message sequence chart with three business partners also called instances. Instances communicate via messages. Messages are either asynchronous (m1, m2, m4, m5, m7, m8, and m9) or synchronous (m3 and m6). Note that a standard message sequence chart does not allow for synchronous messages. We need synchronous messages to model synchronous communication, e.g., a phone call to exchange information. Each message has a sender and a receiver. For example, instance 1 is the sender of m1 and instance 2 is the receiver of m1. For asynchronous messages the message is received by the receiver only after it has been sent by the sender. Each synchronous message results in the synchronization of two instances. Within each instance events are ordered, e.g., instance 3 sends m4 only after the receipt of m2. The ordering of events is specified by the time axis of an instance which is represented by a vertical line. In a message sequence chart, it is also possible to specify coregions. A coregion is represented by a dashed part of the time axis of an instance. Events in a coregion are assumed to be unordered in time. In Figure 6 there is one coregion: the receipt of m4, the receipt of m5, and the sending of m7 are unordered in time.

![Figure 6: A message sequence chart.](image)

In this paper, we consider a variant of message sequence charts as defined in [8] or [18]. The basic message sequence chart has been extended with synchronous messages and coregions. However, for reasons of simplicity, we do not allow for process creation, process termination, timers, and refinement. To formalize the semantics of the message sequence
charts used in this paper, we use a notation adopted from [13].

**Definition 10 (Message sequence chart)** A message sequence chart is a tuple MSC = (I, MA, MS, from, to, {≤}_i),

1. I is a finite set of instances (business partners),
2. MA is a finite set of asynchronous messages,
3. MS is a finite set of synchronous messages,
4. MA ∩ MS = ∅ and M = MA ∪ MS is the set of messages,
5. to and from are functions from M to I,
6. for each i ∈ I: ≤_i is a partial order on {?m | m ∈ MA ∧ to(m) = i} ∪ {!m | m ∈ MA ∧ from(m) = i} ∪ {!?m | m ∈ MS ∧ i ∈ {to(m), from(m)}}.

If m is an asynchronous message, then !m corresponds to the event of sending the message and ?m corresponds to the event of receiving the message. For a synchronous message both instances synchronize on the event !?m. For each instance i, ≤_i specifies the ordering of events along the time axis of i, ≤_i is a partial order instead of a total ordering because of the existence of coregions. In Figure 6, !m1 ≤_1 !?m3, !?m3 ≤_3 !?m4, !?m3 ≤_3 !?m5, !?m3 ≤_3 !?m7, !?m4 ≤_4 !?m8, !?m5 ≤_5 !?m8, !?m7 ≤_7 !?m8, and !?m8 ≤_8 !?m9. Note that the events in the coregion are unordered, e.g., ?m4 ≤_4 !?m7.

**Definition 11 (≤_MSC)** Let MSC = (I, MA, MS, from, to, {≤}_i) be a message sequence chart.

1. ≤_inst = ⋃_{i∈I} ≤_i,
2. ≤_o = {(!m, ?m) | m ∈ MA},
3. ≤_MSC = (≤_inst ∪ ≤_o)_+.

≤_o is a partial order which reflects the production before consumption principle. ≤_MSC is the transitive closure of (1) the partial orders within the instances (≤_inst) and (2) the partial order between the production and consumption of asynchronous messages (≤_o). Consider for example the message sequence chart shown in Figure 6: !m2 ≤_MSC ?m9, !?m3 ≤_MSC ?m8, !m4 ≤_MSC ?m5, !?m8 ≤_MSC ?m9.

A message sequence chart MSC is inconsistent iff ≤_MSC does not define a partial order. In this case, the message sequence chart contains a deadlock due to cyclic dependencies. In the remainder we assume that the message sequence charts are consistent. Note that ≤_MSC is a partial order on A = {?m | m ∈ MA} ∪ {!m | m ∈ MA} ∪ {!?m | m ∈ MS}. A is the set of event labels.
8 Consistency of interorganizational workflows

Message sequence charts can be used to specify the interaction between loosely coupled workflow processes. Such a message sequence chart can be used as a starting point for the design of complex interorganizational workflows. The interorganizational workflow should be designed in such a way that it is consistent with the message sequence chart, i.e., the message sequence chart can be seen as a partial specification of an interorganizational workflow. Therefore, it is interesting to be able to decide whether the implementation (interorganizational workflow) meets the specification (message sequence chart). In this section, we define a notion of consistency and in the next section we present a technique to verify whether an interorganizational workflow is consistent with respect to a message sequence chart.

Definition 12 (\(L\)) Let \(IOWF = (PN_1, PN_2, \ldots, PN_n, PAC, AC, TSC, SC)\) be an interorganizational workflow and \(U(IOWF) = (P^U, T^U, F^U)\). \(L\) is a function from \(T^U\) to the powerset of \(\{?m \mid m \in PAC\} \cup \{!m \mid m \in PAC\} \cup \{!?m \mid m \in TSC\}\). For \(t \in T^U\), \(L(t) = \{?m \mid m \in PAC \land m \in \bullet t\} \cup \{!m \mid m \in PAC \land m \in t\} \cup \{!?m \mid m \in TSC \land m = t\}\).

Function \(L\) maps transitions onto the events associated with the transition. Consider for example the interorganizational workflow shown in Figure 7: \(L(t11) = \{!m1\}, L(t21) = \emptyset, L(t22) = \{?m1, !m2\}, \) and \(L(t24) = \{!m5, !?m6\}\).

In a message sequence chart each message is sent exactly once. Therefore, we introduce the notion of 1-liveness.

Definition 13 (1-live) A transition \(t\) in a Petri net \((PN, M)\) is 1-live iff, (1) for every state \(M'\) reachable without firing \(t\), there is a state \(M''\) reachable from \(M'\) which enables \(t\), and (2) for every state \(M'\) reachable via a firing sequence which fires \(t\), there is no state reachable from \(M'\) which enables \(t\).

In a message sequence chart each message is exchanged between two instances. Therefore, we demand that each communication place in \(PAC\) has one sender and one receiver. Moreover, each transition involved in the communication between instances has to be 1-live. An interorganizational workflow which meets these two requirements is called a restricted interorganizational workflow. Figure 7 shows an example of a restricted interorganizational workflow.

Definition 14 (Restricted IOWF) A restricted interorganizational workflow (RIOWF) is an interorganizational workflow \(IOWF = (PN_1, PN_2, \ldots, PN_n, PAC, AC, TSC, SC)\), which satisfies the following requirements:

(i) for each \((p, x, y) \in AC\): \(x\) and \(y\) are singletons,

(ii) for each transition \(t\) in \(U(IOWF)\): if \(L(t) \neq \emptyset\), then \(t\) is 1-live in \((U(IOWF), i)\).

For restricted interorganizational workflows we define the inverse function of \(L\). \(L^{-1}\) maps each element of \(\{?m \mid m \in PAC\} \cup \{!m \mid m \in PAC\} \cup \{!?m \mid m \in TSC\}\) onto a single transition in \(T^U\).

For restricted interorganizational workflows we define a notion of consistency.
Figure 7: A restricted interorganizational workflow.
Definition 15 (Consistent) Let $IOWF = (PN_1, PN_2, ..., PN_n, P_{AC}, AC, TSC, SC)$ be a restricted interorganizational workflow and let $MSC = (I, M_A, M_S, from, to, \{ \leq \}_{i \in I})$ be a message sequence chart. $IOWF$ is consistent with respect to $MSC$ if and only if

(i) $P_{AC} = M_A$ and $TSC = M_S$,

(ii) $U(IOWF) = (P^U, T^U, F^U)$ is the unfolding of $IOWF$ with source place $i$. For each $t_1, t_2 \in T^U$: if there is a firing sequence starting in state $i$ which fires transition $t_1$ before transition $t_2$, then $\forall a_1 \in \mathcal{L}(t_1) \forall a_2 \in \mathcal{L}(t_2) \neg(a_2 \leq^{MSC} a_1)$.

A restricted interorganizational workflow is consistent with respect to a message sequence chart if the message names used in the message sequence chart correspond to the names of communication elements in the interorganizational workflow and none of the possible firing sequences violates precedence constraints specified in the message sequence chart. The interorganizational workflow shown in Figure 7 is consistent with respect to the message sequence chart shown in Figure 6. However, if place $m9$ connects $t16$ and $t22$ instead of $t16$ and $t25$, then the interorganizational workflow is not consistent with respect to a message sequence chart in Figure 6. The inconsistency is a result of the fact that there is a firing sequence such that $t22$ fires before $t16$, $\exists m9 \in \mathcal{L}(t22)$, $\exists m9 \in \mathcal{L}(t16)$, and ($m9 \leq^{MSC} m9$). Consistency can be verified by generating all possible firing sequences and checking whether the partial order $\leq^{MSC}$ is not violated by any of these sequences. Clearly, consistency is decidable but also very hard to verify if all firing sequences have to be considered. Therefore, we propose a technique to facilitate the verification of consistency.

9 Verification of consistency

A restricted interorganizational workflow is consistent with respect to a message sequence chart if all possible firing sequences satisfy the partial order $\leq^{MSC}$. Instead of checking all possible firing sequences we propose a technique based on the notion of implicit places ([7]). An implicit place, also called a redundant place, is a place which always contains sufficient tokens to allow for the firing of the transitions connected to it. In this paper, we use a generalized notion: the implicit place set.

Definition 16 (Implicit place set) Let $(PN, M)$ be a marked Petri net with $PN = (P, T, F)$ and $P_I \subseteq P$. $P_I$ is an implicit place set if for every reachable state $M'$ and any transition $t \in T$: if each place in $(\bullet t \setminus P_I)$ contains a token in state $M'$, then each place in $(\bullet t \cap P_I)$ contains a token in $M'$. Place $p \in P$ is an implicit place if $\{p\}$ is an implicit place set.

To introduce some basic results for implicit place sets, we define the projection operator ($\uparrow$).

Definition 17 ($\uparrow$) Let $(PN, M)$ be a marked Petri net with $PN = (P, T, F)$ and $P' \subseteq P$.

- $PN \uparrow P' = (P', T, F \cap ((P' \times T) \cup (T \times P')))$. 

17
An implicit place set does not restrict the set of possible firing sequences. Therefore, it can be removed without changing the behavior. Moreover, a set of places is an implicit place set if and only if, each of the places is implicit.

Lemma 2 Let $(PN_1, M_1)$ be a marked Petri net with $PN_1 = (P_1, T_1, F_1)$ and $P_I \subseteq P_1$. Let $(PN_2, M_2) = (PN_1, M_1) \uparrow (P_1 \setminus P_I)$ be the Petri net obtained by removing the places in $P_I$.

(i) $\forall \sigma \in T^* \ M_1[\sigma]_{PN_1} \Rightarrow M_2[\sigma]_{PN_2}$

(ii) If $P_I$ is an implicit place set of $(PN_1, M_1)$, then $\forall \sigma \in T^* \ M_2[\sigma]_{PN_2} \Rightarrow M_1[\sigma]_{PN_1}$.

(iii) $P_I$ is an implicit place set of $(PN_1, M_1)$, if and only if, for all $p \in P_I$: $p$ is an implicit place of $(PN_1, M_1) \uparrow ((P_1 \setminus P_I) \cup \{p\})$.

Proof.
(i) Trivial, removing places does not restrict the set of possible firing sequences.

(ii) Suppose that (ii) does not hold, i.e., $P_I$ is an implicit place set and $\sigma$ is a firing sequence which leads to a state $M'_2$ in $PN_2$ where transition $t$ is enabled and $\sigma$ leads to a state $M'_1$ in $PN_1$ where $t$ is not enabled. Clearly, this is not possible because $P_I$ is an implicit place set.

(iiiia) Suppose that $\Rightarrow$ does not hold, i.e., $P_I$ is an implicit place set but there is a $p$ which is not an implicit place of $(PN_1, M_1) \uparrow ((P_1 \setminus P_I) \cup \{p\})$. There is a firing sequence $\sigma$ in $(PN_1, M_1) \uparrow ((P_1 \setminus P_I) \cup \{p\})$ which leads to a state where a transition $t$ is not enabled ($p$ is empty) but each place in $\bullet t \cap (P_1 \setminus P_I)$ contains a token. $\sigma$ is also a possible firing sequence in $(PN_1, M_1)$ (apply (i) and (ii)). The state reached by firing $\sigma$ in $(PN_1, M_1)$ is such that $t$ is not enabled ($p$ is empty) but each place in $\bullet t \setminus P_I$ is marked. Hence, $P_I$ is not an implicit place set.

(iiiib) Suppose that $\Leftarrow$ does not hold, i.e., for all $p \in P_I$: $p$ is an implicit place of the marked net $(PN_1, M_1) \uparrow ((P_1 \setminus P_I) \cup \{p\})$ but $P_I$ is not an implicit place set. There is a firing sequence $\sigma$ in $(PN_1, M_1)$ which leads to a state such that transition $t$ is not enabled but each place in $\bullet t \cap (P_1 \setminus P_I)$ is marked. This means that there is a $p \in (\bullet t \cap P_I)$ which is not marked. $\sigma$ is also a possible firing sequence in $(PN_1, M_1) \uparrow ((P_1 \setminus P_I) \cup \{p\})$ (apply (i)). The state reached by firing $\sigma$ in $(PN_1, M_1) \uparrow ((P_1 \setminus P_I) \cup \{p\})$ is such that $t$ is not enabled ($p$ is empty) but each place in $\bullet t \setminus \{p\}$ is marked. Hence, $p$ is not an implicit place.

Consistency can be checked via an approach based on implicit place sets. Transitions in a restricted interorganizational workflow are associated with events. A message sequence chart specifies a partial order on these events. Therefore, the message sequence chart indirectly specifies a partial order on transitions. This partial order can be expressed in terms of places connecting transitions. The following theorem shows that these additional places
are implicit, if and only if, the interorganizational workflow is consistent with respect to the message sequence chart.

**Theorem 2** Let \( IOWF = (PN_1, PN_2, ..., PN_n, P_{AC}, AC, T_{SC}, SC) \) be a restricted interorganizational workflow and let \( MSC = (I, M_A, M_S, \text{from}, \text{to}, \{\leq_{i}\}_{i=1}) \) be a message sequence chart such that \( P_{AC} = M_A \) and \( T_{SC} = M_S \). Let \( U(IOWF) = (P^U, T^U, F^U) \) be the unfolding of \( IOWF \) and \( V(IOWF) = (P^V, T^V, F^V) \) a Petri net defined as follows:

- \( P_I = \{(a_1, a_2) \in \leq^{MSC} | \mathcal{L}^{-1}(a_1) \neq \mathcal{L}^{-1}(a_2)\} \) and \( P_V = P_U \cup P_I \).
- \( T_V = T_U \).
- \( F_V = F_U \cup \{(t, p) | p = (a_1, a_2) \in P_I \land t \in T_V \land a_1 \in \mathcal{L}(t)\} \cup \{(p, t) | p = (a_1, a_2) \in P_I \land t \in T_V \land a_2 \in \mathcal{L}(t)\} \).

\( IOWF \) is consistent with respect to \( MSC \), if and only if, \( P_I \) is an implicit place set of \( (V(IOWF), i) \).

**Proof.**
Both the ‘if’ and the ‘only if’ part are proven using contraposition.

(i) Suppose \( IOWF \) is consistent with respect to \( MSC \) and \( P_I \) is not an implicit place set of \( (V(IOWF), i) \). There is place \( p = (a_2, a_1) \in P_I \), a transition \( t_1 \) such that \( p \in \bullet t_1 \), and a possible firing sequence \( \sigma \) such that in the state reached by firing \( \sigma \) all the places in \( \bullet t_1 \cap P_U \) are marked and \( p \) is empty (i.e. transition \( t_1 \) is not enabled). Since \( p \) is a place in \( P_I \), there is just one transition \( t_2 \) which puts tokens in \( p \). Transition \( t_2 \) is the only transition for which \( a_2 \in \mathcal{L}(t_2) \). Note that \( t_1 \neq t_2 \), because \( t_1 = \mathcal{L}^{-1}(a_1), t_2 = \mathcal{L}^{-1}(a_2), \mathcal{L}^{-1}(a_1) \neq \mathcal{L}^{-1}(a_2) \), \( \sigma \) is also a possible firing sequence in \( (U(IOWF), i) \), see Lemma 2(ii). Moreover \( \sigma t_1 \) is a possible firing sequence. Transition \( t_1 \) is 1-live, i.e., in \( \sigma t_1 \) there is precisely one firing of \( t_1 \). Hence \( t_1 \) does not occur in \( \sigma \). In \( (V(IOWF), i) \), \( t_1 \) is the only transition which consumes tokens from \( p \). If \( p \) is empty after firing \( \sigma \), then \( t_2 \) does not occur in \( \sigma \). Because \( t_2 \) is 1-live in \( (U(IOWF), i) \) and \( t_1 \neq t_2 \), it is possible to extend firing sequence \( \sigma t_1 \) into a firing sequence where \( t_1 \) fires before \( t_2 \). Moreover, by the definition of \( P_I, a_2 \leq^{MSC} a_1, a_1 \in \mathcal{L}(t_1) \) and \( a_2 \in \mathcal{L}(t_2) \). Hence, \( IOWF \) is not consistent.

(ii) Suppose \( P_I \) is an implicit place set of \( (V(IOWF), i) \) and \( IOWF \) is not consistent with respect to \( MSC \). There exists a firing sequence \( \sigma \) in \( (U(IOWF), i) \) such that \( t_1 \) fires before \( t_2 \) and there is a \( a_1 \in \mathcal{L}(t_1) \) and \( a_2 \in \mathcal{L}(t_2) \) such that \( a_2 \leq^{MSC} a_1 \). Moreover, \( t_1 \) and \( t_2 \) are 1-live and \( t_1 = \mathcal{L}^{-1}(a_1) \neq \mathcal{L}^{-1}(a_2) = t_2 \). Therefore, \( (a_2, a_1) \in P_I \). \( \sigma \) is also a possible firing sequence of \( (V(IOWF), i) \), see Lemma 2(ii). \( (a_2, a_1) \) is a place in \( V(IOWF) \) which connects \( t_2 \) and \( t_1 \). Transition \( t_2 \) is the only transition which produces tokens for \( (a_2, a_1) \), the input place of \( t_1 \). Therefore, \( t_2 \) has to fire before \( t_1 \) and \( \sigma \) is not a possible firing sequence of \( (V(IOWF), i) \). ∎

Theorem 2 shows that consistency can be verified by checking whether a set of places is implicit. Note that the set \( P_I \) as a whole has to be an implicit place set. It is not sufficient to demand that the individual places in \( P_I \) are implicit. This is the reason we extended the
notion of implicit place to implicit place set. Nevertheless, we can express the notion of implicit place set into the more well-known notion of implicit place (see Lemma 2(iii)).

The observation that consistency corresponds to implicit places allows for the application of well-known Petri-net-based techniques. In fact there are several tools, which allow for the detection of implicit places. Theorem 2 shows that it is not necessary to check whether every possible firing sequence matches the partial order specified by the message sequence chart.

From a computational point of view, verification becomes expensive if there are a lot of places in the set $P_I$, i.e., the are a lot of ordering relations to be checked. However, it is possible to reduce the set $P_I$ to $\leq_{\text{inst}}$ because the ordering imposed by $\leq_{\alpha}$ is already present and the transitive closure follows from the net structure. Therefore, only a limited number of places needs to be checked. Moreover, several authors have investigated techniques to find structural implicit places ([9, 6, 7]). A structural implicit place is a place which is guaranteed to be implicit by the structure of the Petri net. Every structural implicit place is an implicit place, but there may be implicit places which are not structural implicit. Since the set of all structural implicit places can be found without constructing the reachability graph, it allows for very efficient analysis techniques.

The following definition is a generalization of the definition in [7] for implicit place sets.

**Definition 18 (Structural implicit place set)** Let $(PN, M)$ be a marked Petri net with $PN = (P, T, F)$ and $P_I \subseteq P$. $P_I$ is a structural implicit place set iff for each $p \in P_I$ there is a set $Q \subseteq (P \setminus P_I)$ such that:

(i) $M(p) \geq \sum_{q \in Q} M(q)$

(ii) $\forall_{t \in T} X_{tp} \geq \sum_{q \in Q} X_{tq}$, where $X$ is the incidence matrix of $PN$

(iii) $\forall_{t \in T} p \in \bullet t \Rightarrow Q \cap \bullet t \neq \emptyset$

There are several differences with the definition in [7]. First of all, the notion has been extended to sets. Secondly, we only consider nets with arc weights 1. Finally, in (ii) we replaced the equality (=, i.e. place invariant) by $\geq$. It is easy to see that a structural implicit place set is implicit indeed.

**Lemma 3** Let $(PN, M)$ be a marked Petri net with $PN = (P, T, F)$ and $P_I \subseteq P$. If $P_I$ is a structural implicit place set, then $P_I$ is an implicit place set.

As a consequence of Lemma 3, we can prove that an interorganizational workflow is consistent with respect to a message sequence chart by checking whether the set $P_I$ is a structural implicit place set. Consider for example the interorganizational workflow shown in Figure 7. It suffices to consider the structural implicit places to prove that the workflow is consistent with respect to the message sequence chart shown in Figure 6.
10 Conclusion

In this paper, we have shown that a particular kind of interorganizational workflows can be modeled in terms of a set of Petri nets connected via communication elements. We also investigated a basic property that any interorganizational workflow should satisfy: the soundness property. We have seen that this property coincides with well-known Petri net properties. To establish the correctness of an interorganizational workflow composed of \( n \) local workflows, we need to prove liveness and boundedness for \( n + 1 \) WF-nets using standard techniques.

In most cases, the interorganizational workflow should obey a given communication structure in addition to the soundness property. In this paper, we showed that given a message sequence chart which specifies the communication between business partners, it is possible to use an efficient technique to verify whether the interorganizational workflow is consistent with the message sequence chart. This technique uses an extension of the concept of implicit places.

References


In this series appeared:

- 96/01: M. Voorhoeve and T. Basten
- 96/02: P. de Bra and A. Aerts
- 96/03: W.M.P. van der Aalst
- 96/04: S. Mauw
- 96/05: T. Basten and W.M.P. v.d. Aalst
- 96/06: W.M.P. van der Aalst and T. Basten
- 96/07: M. Voorhoeve
- 96/08: A.T.M. Aerts, P.M.E. De Bra, J.T. de Munk
- 96/09: F. Dignum, H. Weigand, E. Verharen
- 96/10: R. Bloo, H. Geuvers
- 96/11: T. Laan
- 96/12: F. Kamareddine and T. Laan
- 96/13: T. Borghuis
- 96/14: S.H.J. Bot and M.A. Reniers
- 96/15: M.A. Reniers and J.J. Vereijken
- 96/17: E. Boiten and P. Hoogendijk
- 96/18: P.D.V. van der Stok
- 96/19: M.A. Reniers
- 96/20: L. Feijs
- 96/21: L. Bijsma and R. Nederpelt
- 96/22: M.C.A. van de Graaf and G.J. Houben
- 96/23: W.M.P. van der Aalst
- 96/24: M. Voorhoeve and W. van der Aalst
- 96/25: M. Vaccari and R.C. Backhouse
- 97/01: B. Knaack and R. Gerth
- 97/02: J. Hoeman and O. v. Roosmalen
- 97/03: J. Blanco and A. v. Deursen
- 97/04: J.C.M. Baeten and J.A. Bergstra
- 97/05: J.C.M. Baeten and J.J. Vereijken
- 97/06: M. Franssen
- 97/07: J.C.M. Baeten and J.A. Bergstra

Below is a list of titles and authors of the papers:

- Process Algebra with Autonomous Actions, p. 12.
- Multi-User Publishing in the Web: DreSS, A Document Repository Service Station, p. 12
- Example specifications in phi-SDL.
- Life-Cycle Inheritance, A Petri-Net-Based Approach, p. 18.
- Structural Petri Net Equivalence, p. 16.
- AUTOMATH and Pure Type Systems, p. 30.
- A Correspondence between Nuprl and the Ramified Theory of Types, p. 12.
- Priorian Tense Logics in Modal Pure Types Systems, p. 61
- The \( I^2 \) C-bus in Discrete-Time Process Algebra, p. 25.
- Completeness in Discrete-Time Process Algebra, p. 139.
- Nested collections and polytypism, p. 11.
- Real-Time Distributed Concurrency Control Algorithms with mixed time constraints, p. 71.
- Static Semantics of Message Sequence Charts, p. 71
- Algebraic Specification and Simulation of Lazy Functional Programs in a concurrent Environment, p. 27.
- Designing Effective Workflow Management Processes, p. 22.
- Structural Characterizations of sound workflow nets, p. 22.
- Conservative Adaptation of Workflow, p. 22
- Deriving a systolic regular language recognizer, p. 28
- Basic Conditional Process Algebra, p. 20.
- Bounded Stacks, Bags and Queues, p. 15.
<table>
<thead>
<tr>
<th>Date</th>
<th>Authors</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>97/08</td>
<td>P. Hoogendijk and R.C. Backhouse</td>
<td>When do datatypes commute?</td>
<td>35.</td>
</tr>
<tr>
<td>97/09</td>
<td>Proceedings of the Second International</td>
<td>Communication Modeling: The Language/Action Perspective</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>Workshop on Communication Modeling,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E.H.L. Aarts</td>
<td>design model.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aalst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>97/13</td>
<td>W.M.P. van der Aalst</td>
<td>Exploring the Process Dimension of Workflow Management</td>
<td>56.</td>
</tr>
<tr>
<td>97/14</td>
<td>J.F. Groote, F. Monin and J. Springintveld</td>
<td>A computer checked algebraic verification of a distributed summation</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>algorithm.</td>
<td></td>
</tr>
<tr>
<td>97/15</td>
<td>M. Franssen</td>
<td>\texttt{\lambda P}\texttt{- A Pure Type System for First Order}</td>
<td>35.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Logic with Automated Theorem Proving</td>
<td></td>
</tr>
</tbody>
</table>