A Trace-Based View on Operating Guidelines

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Abstract. *Operating guidelines* have been introduced to characterize all controllers for a given service S . A controller of S is a service that interacts with S without deadlocking. An operating guideline of S can be used to decide whether S *refines* another service. It is a special-purpose structure to describe the behavior of service S from the perspective of its controllers rather than from the perspective of S .

This paper provides a more conceptual understanding of operating guidelines from the perspective of a traditional concurrency semantics: *a trace-based semantics*. As benefits, we get an easier characterization of service refinement, and prove that this is a fully abstract precongruence.

1 Introduction

Service-oriented computing (SOC) [14] is a computing paradigm that has found growing acceptance in industry. A service-oriented system is a distributed system that is aggregated from building blocks, called *services*. A service encapsulates a certain functionality and offers it to other services over a well-defined interface. The distributed nature of service-oriented systems requires services to interact with each other via *asynchronous* message passing.

Service orientation supports the shift from monolithic systems to systems in which multiple organizations are involved, and it allows faster changes than in monolithic systems. The latter requires a notion of *service replaceability*. Replacing one service with another one has to preserve correctness of the overall system (*compositionality*). Because organizations usually do not know the services involved in the system, replacement must be independent of a service context; that is, for every context a service correctly interacts with, the replacement must correctly interact with as well. We refer to such a context as a *controller*.

A minimal requirement for the correctness of a system is the absence of deadlocks — that is, of unsuccessful termination. The replacement (or refinement) relation in the context of deadlock freedom has been formalized by the *accordance preorder* in [15]. The current decision procedure uses that, for finite-state services with bounded buffers, the set of controllers has a finite representation, the *operating guideline* [8] of the service; technically, it is an automaton annotated with Boolean formulae. Deciding accordance of two services is reduced to

checking that one of the corresponding operating guidelines simulates the other and that the corresponding formulae of related states imply each other.

This characterization of accordance differs from existing refinement relations, because the special-purpose operating guideline describes the service behavior from the perspective of a controller and has an unusual nature. This makes operating guidelines more difficult to understand. In addition, it raises the question how the semantics of an operating guideline and hence the accordance preorder are related to existing refinement notions in literature. Another open question is whether accordance is a precongruence w.r.t. composition.

This paper answers these questions. First, we show that the behavior of a service can be characterized by four trace sets — somewhat similar to standard or completed traces, and to catastrophic traces in the spirit of divergence traces [2]. This semantics naturally gives rise to a refinement relation, which we prove to coincide with (a slight modification of) accordance. Like in [8,15], we use Petri nets to model finite state services; however, as a further improvement, we consider a more general notion of finite state service than in [8,15,9].

Second, our modified accordance relation is more uniform than the original accordance relation. In particular, the semantics of a composition can be determined from the semantics of the components, which proves that this relation is a precongruence w.r.t. composition. The latter can also be phrased as a full abstractness result. We further sketch how accordance can be decided in practice.

Third, we show explicitly how (automaton representations of) the new semantics can be translated back and forth into operating guidelines. This allows us to take a different view on operating guidelines.

Section 2 gives some background, Sect. 3 introduces an accordance relation for infinite state services and characterizes its semantics using traces. In Sect. 4, we present our results concerning accordance for finite state services. Section 5 compares operating guidelines and our trace-based semantics. We close with a discussion of related work and a conclusion.

2 Preliminaries

As a basic model, we use place/transition Petri nets extended with final markings and transition labels. For sets A and B , $A \uplus B$ denotes the disjoint union; writing $A \uplus B$ expresses the implicit assumption that A and B are disjoint.

Definition 1 (net). A *net* $N = (P, T, F, m_N, \Omega)$ consists of a finite set P of *places*, a finite set T of *transitions* such that P and T are disjoint, a *flow relation* $F \subseteq (P \times T) \cup (T \times P)$, an *initial marking* m_N , where a marking is a mapping $m : P \rightarrow \mathbb{N}$, and a set Ω of *final markings*.

A *labeled net* is a net N together with an *alphabet* Σ of actions and a *labeling function* $l : T \rightarrow \Sigma \uplus \{\tau\}$, where τ represents an invisible, internal action.

Introducing N implicitly introduces its components P, T, F, m_N, Ω ; the same applies to N' , N_1 , etc. and their components $P', T', \dots$, and $P_1, T_1, \dots$, resp. — and it also applies to other structures later on. We use the standard graphical

representation, writing transition labels $\neq \tau$ into the respective boxes. The *preset* of $x \in P \cup T$ is $\bullet x = \{y \mid (y, x) \in F\}$ and the *postset* is $x^\bullet = \{y \mid (x, y) \in F\}$. We interpret pre- and postsets as multisets when used in operations with multisets.

For a word $w \in \Sigma_1^*$ and $\Sigma_2 \subseteq \Sigma_1$, $w|_{\Sigma_2}$ denotes the projection of w to the subalphabet Σ_2 . With $v \sqsubseteq w$ we denote that v is a *prefix* of word w , and $\text{cont}(L) = \{w \in \Sigma^* \mid \exists v \in L : v \sqsubseteq w\}$ is the set of all *continuations* of language $L \subseteq \Sigma^*$.

A marking is a multiset over P ; for example, $[p_1, 2p_2]$ denotes a marking m with $m(p_1) = 1$, $m(p_2) = 2$, and $m(p) = 0$ for $p \in P \setminus \{p_1, p_2\}$. We define $+$ and $-$ for the sum and the difference of two markings and $=, <, >, \leq, \geq$ for comparison of markings in the standard way. A marking is changed by *firing* a transition. A transition t is *enabled* at a marking m , denoted by $m \xrightarrow{t}$, if $m \geq \bullet t$. Then, t can *fire*, reaching a marking m' (denoted by $m \xrightarrow{t} m'$), where $m' = m - \bullet t + t^\bullet$.

The behavior of N can be extended to sequences: $m_1 \xrightarrow{t_1} m_2 \xrightarrow{t_2} \dots m_k$ is a *run* of N if $m_i \xrightarrow{t_i} m_{i+1}$, for all $0 < i < k$. A marking m' is *reachable from* a marking m if there exists a (possibly empty) run $m_1 \xrightarrow{t_1} \dots \xrightarrow{t_{k-1}} m_k$ with $m = m_1$ and $m' = m_k$; for $w = t_1 \dots t_{k_1}$ we also write $m_1 \xrightarrow{w} m_k$. Marking m' is *reachable* if $m_N = m$. In the case of labeled nets, we lift runs to traces: If $m_1 \xrightarrow{w} m_k$ and v is obtained from w by replacing each transition by its label and removing all τ labels, we write $m_1 \xRightarrow{v} m_k$ and call v a *trace* whenever $m_1 = m_N$. A marking m is *stable* if it does not enable a τ -labeled transition. The *reachability graph* $RG(N)$ of N has the reachable markings as its nodes and a t -labeled edge from m to m' whenever $m \xrightarrow{t} m'$. In the case of a labeled net, each edge label t is replaced by $l(t)$.

Finally, we introduce two properties of nets. A net N is *b-bounded* for $b \in \mathbb{N}$ if $m(p) \leq b$ for every reachable marking m and $p \in P$; N is *bounded* if it is b -bounded for some $b \in \mathbb{N}$. A reachable marking $m \notin \Omega$ of N is a *deadlock* if no transition $t \in T$ of N is enabled at m .

2.1 Open Nets

Like in [8,15], we model services as *open nets* [16,8], thereby restricting ourselves (like in [8,15]) to the communication protocol of a service. An open net extends a net by an interface. An interface consists of two disjoint sets of input and output places corresponding to asynchronous input and output channels. In the initial marking and the final markings, interface places are not marked. An input place has an empty preset, whereas an output place has an empty postset.

Definition 2 (open net). An *open net* N is a tuple $(P, T, F, m_N, I, O, \Omega)$ with

- $(P \uplus I \uplus O, T, F, m_N, \Omega)$ is a net;
- for all $p \in I \uplus O$: $m_N(p) = 0$ and for all $m \in \Omega$: $m(p) = 0$;
- the set I of *input places* satisfies $\bullet p = \emptyset$ for all $p \in I$; and
- the set O of *output places* satisfies $p^\bullet = \emptyset$ for all $p \in O$.

Two open nets are *interface equivalent* if they have the same sets of input and output places. If $I = O = \emptyset$, then N is a *closed net*. The net that results from removing the interface places and their adjacent arcs from N is *inner*(N).

Fig. 1. Two open nets, their environments, and their composition

Graphically, we represent an open net like a net with a dashed frame around it. The interface places are depicted on the frame.

For the composition of open nets, we assume that the sets of transitions are pairwise disjoint and that no internal place of an open net is a place of any other open net. The interfaces intentionally overlap. We require that all communication is *bilateral* and *directed*; that is, every shared place p has only one open net that sends into p and one open net that receives from p . We refer to open nets that fulfill these properties as *composable*. We compose two composable open nets N_1 and N_2 by merging those interface places they have in common and turn these places into internal places.

Definition 3 (open net composition). Open nets N_1 and N_2 are *composable* if $(P_1 \uplus T_1 \uplus I_1 \uplus O_1) \cap (P_2 \uplus T_2 \uplus I_2 \uplus O_2) = (I_1 \cap O_2) \uplus (I_2 \cap O_1)$. The *composition* of two composable open nets N_1 and N_2 is the open net $N_1 \oplus N_2 = (P, T, F, m_N, I, O, \Omega)$, where

- $P = P_1 \uplus P_2 \uplus (I_1 \cap O_2) \uplus (I_2 \cap O_1)$; $T = T_1 \uplus T_2$; $F = F_1 \uplus F_2$;
- $m_N = m_{N_1} + m_{N_2}$, extending m_{N_i} with $m_{N_i}(p) = 0 \ \forall p \in P_{3-i}, i = 1, 2$;
- $I = (I_1 \uplus I_2) \setminus (O_1 \uplus O_2)$; $O = (O_1 \uplus O_2) \setminus (I_1 \uplus I_2)$; and
- $\Omega = \{m_1 + m_2 \mid m_1 \in \Omega_1 \wedge m_2 \in \Omega_2\}$.

Example 1. Figure 1 shows two composable open nets N_1 and N_2 and their composition $N_1 \oplus N_2$. The composition is still an open net.

2.2 Environments

To give an open net N a trace-based semantics, we consider its environment $env(N)$ similarly as in [16]. The net $env(N)$ can be constructed from N by adding to each interface place $p \in I$ ($p \in O$) a p -labeled transition p in $env(N)$ and renaming place p by p^i (p^o). This way, the asynchronous interface of N is translated into a buffered synchronous interface described by the transition labels of $env(N)$.

Definition 4 (open net environment). The *environment of an open net* N is the labeled net $env(N) = (P \uplus P^I \uplus P^O, T \uplus I \uplus O, F', m_N, \Omega, I \uplus O, l')$, where

- $P^I = \{p^i \mid p \in I\}$; $P^O = \{p^o \mid p \in O\}$;
- $F' = ((P \cup T) \times (T \cup P)) \cap F$
 $\cup \{(p^i, t) \mid p \in I, t \in T, (p, t) \in F\} \cup \{(t, p^o) \mid p \in O, t \in T, (t, p) \in F\}$
 $\cup \{(p^o, p) \mid p \in O\} \cup \{(p, p^i) \mid p \in I\}$; and
- $l'(t) = \begin{cases} \tau, & t \in T \\ t, & t \in I \cup O. \end{cases}$

The language of N is defined by $L(N) = \{w \in (I \uplus O)^* \mid m_{env(N)} \xrightarrow{w}\}$.

To compose environments of composable open nets, we define a parallel composition $\uparrow$, where, for each action a that the components have in common, each a -labeled transition of one component is synchronized with each a -labeled transition of the other; afterward a is hidden. Because a itself is the only a -labeled transition, the definition can be simplified compared to a more general setting, for instance in [16].

Definition 5 (parallel composition). Let $env(N_1) = (P_1, T_1, F_1, m_{N_1}, \Omega_1, \Sigma_1, l_1)$ and $env(N_2) = (P_2, T_2, F_2, m_{N_2}, \Omega_2, \Sigma_2, l_2)$ be the environments of composable open nets N_1 and N_2 . The *parallel composition* of $env(N_1)$ and $env(N_2)$ is defined by the labeled net $env(N_1) \uparrow env(N_2) = (P, T, F, m_N, \Omega, \Sigma, l)$, where

- $P = P_1 \uplus P_2$; $T = T_1 \cup T_2$;
- $F = F_1 \uplus F_2$; $m_N = m_{N_1} + m_{N_2}$;
- $\Omega = \{m_1 + m_2 \mid m_1 \in \Omega_1 \wedge m_2 \in \Omega_2\}$; $\Sigma = (\Sigma_1 \cup \Sigma_2) \setminus (\Sigma_1 \cap \Sigma_2)$; and
- $l(t) = \begin{cases} l_1(t), & t \in (T_1 \setminus T_2) \\ l_2(t), & t \in (T_2 \setminus T_1) \\ \tau, & \text{otherwise.} \end{cases}$

Example 2. Figure 1 depicts environment $env(N_1)$ and $env(N_2)$ of open nets N_1 and N_2 and their parallel composition $env(N_1) \uparrow env(N_2)$. $L(N_1) = b^* + b^*ab^*$ and $L(N_2) = a^*$.

To describe the behavior of compositions, we define parallel compositions of words and languages; operator $\parallel$ synchronizes common actions, operator $\uparrow$ also hides them. Observe that, in $env(N_1) \uparrow env(N_2)$, just common transitions are merged; operator $\parallel$ is needed to relate the respective transition sequences.

Definition 6. Given alphabets $\Sigma_1, \Sigma_2, \Sigma = (\Sigma_1 \cup \Sigma_2) \setminus (\Sigma_1 \cap \Sigma_2)$, words $w_1 \in \Sigma_1^*$ and $w_2 \in \Sigma_2^*$, and languages $L_1 \subseteq \Sigma_1^*$ and $L_2 \subseteq \Sigma_2^*$, we define

- $w_1 \parallel w_2 = \{w \in (\Sigma_1 \cup \Sigma_2)^* \mid w|_{\Sigma_1} = w_1 \wedge w|_{\Sigma_2} = w_2\}$;
- $w_1 \uparrow w_2 = \{w|_{\Sigma} \mid w \in w_1 \parallel w_2\}$;
- $L_1 \parallel L_2 = \bigcup \{w_1 \parallel w_2 \mid w_1 \in L_1 \wedge w_2 \in L_2\}$; and
- $L_1 \uparrow L_2 = \bigcup \{w_1 \uparrow w_2 \mid w_1 \in L_1 \wedge w_2 \in L_2\}$.

3 Trace Semantics for Deadlock Freedom

This section considers the intuitive idea that the communication of a user with a service is successful if it only stops in case of successful termination; that is, the composition is in a final state. Such a user can also be seen as a *controller* of the service. When refining an open net $Spec$, understood as a service specification, to an implementing open net $Impl$, we require that every satisfied user of $Spec$ should also be satisfied with $Impl$. Our aim is to characterize this refinement relation without considering users or controllers explicitly, and to show that the relation is a precongruence for $\oplus$; that is, it supports compositional reasoning.

Definition 7 (controller, accordance). An open net C is a *controller* of an open net N if the composition $N \oplus C$ is a closed net without deadlocks.

Let $Spec$ and $Impl$ be interface equivalent open nets. Open net $Impl$ *accords* with open net $Spec$, denoted by $Impl \sqsubseteq_{acc} Spec$, if every controller C of $Spec$ is also a controller of $Impl$.

Accordance has been defined in [15] for finite state services; that is, the composition of N and a controller must be a bounded net. The unbounded case is interesting in its own right, and it is simpler in theory and prepares the approach for the bounded case.

3.1 Stop-Dead Semantics

Our new semantics of an open net N considers two sets of traces for its environment $env(N)$. A *stop-trace* records a run of $env(N)$ that ends in a marking m enabling transitions of I only; it is a *dead-trace* if in addition m is not a final marking.

Definition 8 (stop-dead (sd) semantics). Let N be an open net. Marking m of $env(N)$ is a *stop except for inputs* if $\forall t : m \xrightarrow{t}$ implies $t \in I$. Define

- $stop(N) = \{w \mid m_{env(N)} \xrightarrow{w} m \text{ and } m \text{ is a stop except for inputs}\}$ and
- $dead(N) = \{w \mid m_{env(N)} \xrightarrow{w} m \notin \Omega \text{ and } m \text{ is a stop except for inputs}\}.$

With this semantics, we can characterize when a closed net has a deadlock.

Proposition 9. *A closed net N has a deadlock iff $dead(N) = \{\epsilon\}$.*

We study now how the sd-semantics of two open nets can be combined to obtain the sd-semantics of their composition. For the rest of this section, we fix two composable open nets $N_1 = (P_1, T_1, F_1, m_{N_1}, I_1, O_1, \Omega_1)$ and $N_2 = (P_2, T_2, F_2, m_{N_2}, I_2, O_2, \Omega_2)$, and we define $E = env(N_1) \uparrow env(N_2)$. Note that $env(N_1 \oplus N_2)$ and E have the same places except for the $p \in (I_1 \cap O_2) \cup (I_2 \cap O_1)$ in $env(N_1 \oplus N_2)$ and the corresponding p^i, p^o in E .

Theorem 10 (sd-semantics for open net composition). *For composable open nets N_1 and N_2 , we have*

1. $L(N_1 \oplus N_2) = L(N_1) \uparrow L(N_2);$
2. $stop(N_1 \oplus N_2) = stop(N_1) \uparrow stop(N_2);$ and
3. $dead(N_1 \oplus N_2) = (dead(N_1) \uparrow stop(N_2)) \cup (stop(N_1) \uparrow dead(N_2)).$

3.2 Coincidence with Accordance

We define a refinement relation between open nets based on their sd-semantics. From Theorem 10, it is preserved under $\oplus$; that is, it is a precongruence.

Definition 11 (sd-refinement). For any two interface equivalent open nets $Spec$ and $Impl$, $Impl$ *sd-refines* $Spec$, denoted by $Impl \sqsubseteq_{sd} Spec$, iff $dead(Impl) \subseteq dead(Spec) \wedge stop(Impl) \subseteq stop(Spec)$.

Theorem 12 (precongruence). *Relation $\sqsubseteq_{sd}$ is a precongruence for $\oplus$.*

Next, we prove that the notion of accordance coincides with sd-refinement, and get a precongruence result as an easy corollary.

Theorem 13 (accordance and sd-refinement coincide). *For interface equivalent open nets $Spec$ and $Impl$, we have $Impl \sqsubseteq_{acc} Spec \Leftrightarrow Impl \sqsubseteq_{sd} Spec$.*

Corollary 14. *Accordance is a precongruence for composition operator $\oplus$.*

4 Trace Semantics for Deadlock Freedom and Boundedness

In this section, we restrict ourselves to finite state services — more precisely, a composition with a controller must be b -bounded for some $b \in \mathbb{N} \setminus \{0\}$. The motivation for this restriction is that we model the control flow of service compositions and assume a (finite) capacity of the message channels. To ensure boundedness in the composition, controllers must not send a message if there are already b messages in the respective message channel, but they must also avoid bound violations on interior places. Technically, parameter b enforces that the composition has a finite number of reachable states. Pragmatically, it could either represent a reasonable buffer size in the middleware — for example, the result of a static analysis of the communication behavior of a service — or be chosen sufficiently large.

Definition 15 (b-controllability). Let $b \in \mathbb{N} \setminus \{0\}$. An open net C *b-controls* an open net N if the composition $N \oplus C$ is closed, deadlock-free, and b -bounded.

Different from [8], we also prescribe bound b for the interior of services and controllers. Instead, only boundedness with possibly varying bounds is required in [8]. That this requirement is weaker is of little relevance¹, but it can create problems, because interface places turn into interior places of a composition. More importantly, boundedness is required in [8] for the inner of services and controllers on their own — that is, with unlimited input tokens in particular. We are more general, because we allow services (and users) that have an unbounded

¹ In principle, one can determine the state space of such a bounded open net and transform it into an automaton (such automata are studied in [8], for example) and, thus, into an open net which has even a 1-bounded inner.

inner; we only require that they are b -bounded in suitable contexts. Thus, we are more optimistic in the sense of [3], because we assume that the controller will steer the service away from bound violations.

We lift accordance for open nets to b -accordance by comparing b -controllers only. In [15], 1-accordance has been defined for controllers as defined in [8].

Definition 16 (b-accordance). For interface equivalent open nets $Spec$ and $Impl$, $Impl$ b -accords with $Spec$, denoted by $Impl \sqsubseteq_{acc}^b Spec$, if $\forall C : C$ b -controls $Spec$ implies C b -controls $Impl$.

In the remainder of this section, we extend the sd-semantics of open nets taking into account the bound. With the new semantics, we define a refinement relation between open nets and prove that it coincides with b -accordance.

4.1 Bounded Stop-Dead Semantics

The idea is to specify a set $bd_b(N)$ containing all traces of $env(N)$ that lead to a marking violating bound b . We refer to such a trace v as a *bound-violator*. As we want to forbid such a trace, a continuation w of v is automatically forbidden as well; thus, it is irrelevant whether w is a bound-violator or can be performed at all. Technically, this abstraction from continuations is achieved by including all continuations of bound-violators in $bd_b(N)$. For the same reason, $bd_b(N)$ is contained in all other components of our semantics. This is similar to the treatment of divergence traces in failures semantics [2] and also of $U(N)$ in [16, Def. 3.3.2] — for a setting with synchronous communication in both cases.

Definition 17 (bounded stop-dead (bsd-) semantics). Let $b \in \mathbb{N} \setminus \{0\}$. For an open net $N = (P, T, F, m_N, I, O, \Omega)$ with environment $env(N)$, we call a trace v a *bound $_b$ -violation* of N if $m_{env(N)} \xrightarrow{v} m \wedge \exists p \in P \cup I \cup O : m(p) > b$.

- $bd_b(N) = \{w \in (I \cup O)^* \mid \exists v \sqsubseteq w : v \text{ is a bound}_b\text{-violation}\}$,
- $L_b(N) = L(N) \cup bd_b(N)$,
- $stop_b(N) = stop(N) \cup bd_b(N)$, and
- $dead_b(N) = dead(N) \cup bd_b(N)$.

Just as $stop(N_1)$ is needed to determine $dead(N_1 \oplus N_2)$, $L_b(N_1)$ will be needed to determine $bd_b(N_1 \oplus N_2)$.

We characterize the bsd-semantics of the composition of two open nets based on their bsd-semantics, enforcing continuation closure of $bd_b(N_1 \oplus N_2)$ explicitly.

Theorem 18 (bsd-semantics for open net composition). For composable open nets N_1 and N_2 we have

1. $bd_b(N_1 \oplus N_2) = cont((bd_b(N_1) \uparrow L_b(N_2)) \cup (L_b(N_1) \uparrow bd_b(N_2)))$
2. $L_b(N_1 \oplus N_2) = (L_b(N_1) \uparrow L_b(N_2)) \cup bd_b(N_1 \oplus N_2)$
3. $stop_b(N_1 \oplus N_2) = (stop_b(N_1) \uparrow stop_b(N_2)) \cup bd_b(N_1 \oplus N_2)$
4. $dead_b(N_1 \oplus N_2) = (stop_b(N_1) \uparrow dead_b(N_2)) \cup (dead_b(N_1) \uparrow stop_b(N_2)) \cup bd_b(N_1 \oplus N_2)$

4.2 Coincidence with b -Accordance and Nonredundancy

Analogously to sd -refinement, we define bsd -refinement and conclude from Theorem 18(1) to (4) that it is preserved under the composition operator $\oplus$.

Definition 19 (bsd -refinement). For interface equivalent open nets Spec and Impl and a bound $b \in \mathbb{N} \setminus \{0\}$, Impl bsd_b -refines Spec , denoted by $\text{Impl} \sqsubseteq_{\text{bsd},b} \text{Spec}$, if $L_b(\text{Impl}) \subseteq L_b(\text{Spec}) \wedge \text{dead}_b(\text{Impl}) \subseteq \text{dead}_b(\text{Spec}) \wedge \text{stop}_b(\text{Impl}) \subseteq \text{stop}_b(\text{Spec}) \wedge \text{bd}_b(\text{Impl}) \subseteq \text{bd}_b(\text{Spec})$.

Theorem 20 (precongruence). For each $b \in \mathbb{N} \setminus \{0\}$, bsd_b -refinement is a precongruence for composition operator $\oplus$.

Each refinement relation b -accordance (see Definition 16) coincides with bsd_b -refinement, which implies a novel precongruence result as a corollary. The main point for the latter result is that we have a more uniform approach compared to [8], where in Definition 15 the interface places of N and C play a special role in $N \oplus C$ although they are ordinary places of this closed net. In fact, b -accordance, as introduced in [15], is no precongruence for our composition operator $\oplus$. Corollary 22 could also be proved directly by a standard argument, as presented in a very general setting in [13].

Theorem 21 ($\sqsubseteq_{\text{acc},b}$ and $\sqsubseteq_{\text{bsd},b}$ coincide). For interface equivalent open nets Spec and Impl and a bound $b \in \mathbb{N} \setminus \{0\}$ holds $\text{Impl} \sqsubseteq_{\text{acc},b} \text{Spec} \Leftrightarrow \text{Impl} \sqsubseteq_{\text{bsd},b} \text{Spec}$.

Corollary 22. For each $b \in \mathbb{N} \setminus \{0\}$, b -accordance is a precongruence for $\oplus$.

As the bsd -semantics consists of four overlapping components, the question arises whether each of them is really needed. In particular, one might suspect that the set L_b can be obtained from the other three sets by taking prefixes. To answer this question, one can construct examples showing that none of the components can be deduced from the others.

4.3 Full Abstractness

We can present the results of Sect. 4.2 also as a *full abstractness* result [11]; that is, b -accordance is the coarsest precongruence for open nets w.r.t. a suitable basic relation $\sqsubseteq_b$ and composition operator $\oplus$. It is somewhat unusual that this basic relation is only defined for closed nets: $\text{Impl} \sqsubseteq_b \text{Spec}$ says that Impl must represent a ‘good’ communication if Spec does.

Definition 23 (basic relation). For closed open nets Spec and Impl and a bound $b \in \mathbb{N} \setminus \{0\}$, define the *basic relation* $\text{Impl} \sqsubseteq_b \text{Spec}$ iff whenever Spec cannot deadlock and does not violate bound b so does Impl .

Relation $\sqsubseteq_b^c$ is the *coarsest precongruence* for $\oplus$ such that for all closed Impl and Spec : $\text{Impl} \sqsubseteq_b^c \text{Spec}$ implies $\text{Impl} \sqsubseteq_b \text{Spec}$.

Theorem 24 ($\sqsubseteq_{\text{acc},b}$ is fully abstract). For interface equivalent open nets Spec and Impl and a bound $b \in \mathbb{N} \setminus \{0\}$ holds $\text{Impl} \sqsubseteq_{\text{acc},b} \text{Spec} \Leftrightarrow \text{Impl} \sqsubseteq_b^c \text{Spec}$.

4.4 Deciding *bsd*-Refinement

To decide *bsd*-refinement between two open nets, four language inclusions must be checked. We discuss a decision procedure for *bsd*-refinement, also to prepare the comparison to the standard approach for deciding *b*-accordance (see [15]), which is based on operating guidelines [8].

For deciding the four language inclusions, we build one automaton with four types of final states. To do this, we construct the reachability graph of the labeled net $env(N)$ under consideration, but stop the construction whenever we reach a marking m that violates the bound b . As any bounded net has only finitely many reachable markings, this guarantees finiteness of our construction. Each such marking m gets a loop for each visible label from $I \cup O$. The initial state of the automaton is the initial marking $m_{env(N)}$.

This way, the automaton has $bd_b(N)$ as language if we designate each m that violates b as final state. If we additionally take those markings m as final states that are stops except for inputs and not in the set Ω of final markings, then the language is $dead_b(N)$. If we add all markings m as final states that are stops except for inputs, then the language is $stop_b(N)$. Finally, letting all states be final, the language is $L_b(N)$.

If we label the final states added in the four stages with 0, 1, 2, 3, then, for each state, we need two additional bits for encoding the four languages. We use

- 0 to describe the language $bd_b(N)$;
- 0 and 1 to describe the language $dead_b(N)$;
- 0, 1, and 2 to describe the language $stop_b(N)$; and
- 0, 1, 2, and 3 to describe the language $L_b(N)$.

For checking language inclusion, one makes at least the automaton for the larger language deterministic (by constructing the powerset automaton) and constructs the (unique minimal) simulation [12] between the two automata. Practically, this powerset construction often leads to smaller automata. In our case, it suffices to apply this construction once — although we have four languages. A similar construction is used when building a lexer, for instance. Here, we refer to a version of the powerset construction that also removes τ -transitions — that is, ϵ -transitions according to automata theory.

Each set of states, as state of the powerset automaton, is a *node* and is labeled with the minimum label of its states. As a further simplification, one can identify all nodes with label 0 into one node U . This identification is integrated into the powerset construction. We refer to the resulting automaton as $BSD_b(N)$.

To decide *bsd*-refinement of two open nets *Spec* and *Impl*, we calculate the minimal simulation ϱ of $BSD_b(Impl)$ by $BSD_b(Spec)$ and check the labels of related states as stated next; one could also consider the minimal simulation of the modified reachability graph of *Impl*, as described previously, by $BSD_b(Spec)$.

Theorem 25 (deciding *bsd*-refinement). *For interface equivalent open nets $Spec$ and $Impl$ and a bound $b \in \mathbb{N} \setminus \{0\}$, we have $Impl \sqsubseteq_{bsd,b} Spec$ iff the minimal simulation of $BSD_b(Impl)$ by $BSD_b(Spec)$ exists and relates a node of $BSD_b(Impl)$ with label i only to nodes of $BSD_b(Spec)$ with label $j \leq i$.*

5 Comparing *bsd*-Semantics and Operating Guidelines

We compare the *bsd*-semantics of Definition 17 with the notion of an operating guideline [8] for open nets N . An operating guideline $OG_b(N)$ of a service N describes how a *user* should successfully communicate with N ; technically, it characterizes the possibly infinite set of b -controllers of N in a finite manner. Because a b -controller of N provides suitable inputs for N and accepts its outputs, $OG_b(N)$ is similar to $BSD_b(N)$ but with inputs and outputs interchanged.

The operating guidelines of two open nets $Spec$ and $Impl$ can be used to decide that $Impl$ b -accords with $Spec$ [15]. Thus, $OG_b(N)$ and $BSD_b(N)$ should have the same semantic content. As their details are rather different, we clarify their relation by showing how to translate $OG_b(N)$ and $BSD_b(N)$ into each other. These translations do not make use of the states contained in the nodes, but the correctness proof for the translations does; for example, the node labels are defined on the basis of these states.

Operating guidelines have been defined only for services N with b -bounded interface for which $inner(N)$ is bounded. As these two bounds are not necessarily the same, we restrict the translation to services N where $inner(N)$ is b -bounded.

5.1 Deriving an Operating Guideline from the *bsd*-Semantics

Both $OG_b(N)$ and $BSD_b(N)$ are finite automata that can be distinguished by their graph structure and annotations.

Graph structure. There are two differences in the graph structure of $OG_b(N)$ and $BSD_b(N)$. First, a b -controller may be able to accept inputs that N will never send. As a consequence, $OG_b(N)$ contains an additional node, the *empty node* (which does not contain any state). For each output $x \in O$ of N and each node without an outgoing x -labeled edge in $BSD_b(N)$, there is a respective edge leading to the empty node, and this node has loops for all possible visible actions from $I \cup O$. Because $BSD_b(N)$ represents the behavior of N rather than the behavior of its b -controllers, the empty node does not exist in $BSD_b(N)$. To ease the presentation, we ignore the empty node in the following.

Second, node U , which identifies all nodes with label 0 in $BSD_b(N)$, is not present in $OG_b(N)$. Because $OG_b(N)$ characterizes all b -controllers, possible bound violations will not happen and, hence, do not need to be stored. It is easy to omit U from $BSD_b(N)$, as it is identified by label 0. Vice versa, it is also possible to add U to $OG_b(N)$ by adding, for each input $a \in I$ of N to each node of $OG_b(N)$ without an outgoing a -labeled edge, such an edge leading to U . In addition, node U has like the empty node loops for all visible actions. Note that the empty node and node U are characterized in their respective automaton by having a loop for a respective output action, leading to behavior that certainly violates any bound b .

Annotations. Instead of the remaining node labels 1, 2, 3 in $BSD_b(N)$, each node Q of $OG_b(N)$ is annotated with a Boolean formula $\phi(Q)$. The propositional

atoms of ϕ are $I \cup O \cup \{final\}$. A b -controller cannot know which state q of a node Q net $env(N)$ might be in, but it has to avoid a deadlock and a bound violation in any case; the formula $\phi(Q)$ describes how to do this. Nonstable states have an internal transition and, thus, are not deadlocks; all internal transitions remain in the same node. As a consequence, $\phi(Q)$ is a *conjunction indexed by all stable states* $q \in Q$. Every conjunct is a disjunction of the following propositional atoms: $final$ if q is a final state, $a \in I$ if $Q \xrightarrow{a}$, and $x \in O_N$ if $q \xrightarrow{x}$. Hence, the formulae are in conjunctive normal form (CNF) without negation.

To construct $\phi(Q)$ from $BSD_b(N)$ (up to equivalence), we need a procedure to which we refer to as *1,2-DFS*. This procedure is something like a depth-first search through the automaton starting from node Q . It considers only x -labeled edges with $x \in O_N$ and backtracks if (and only if) there is no further such edge or when encountering a 1,2-node (i.e., a node labeled 1 or 2); that is, visited states are not marked as visited in this procedure. When a 1,2-node is encountered, the path in the stack is called a *maximal path constructed during 1,2-DFS*. One can see that 1,2-DFS never encounters node U , because edges leading to U are input edges of N . Also note that 1,2-DFS cannot run into a cycle; if $Q \xrightarrow{x} Q'$, then Q' consists of all q' such that $\exists q \in Q : q \xrightarrow{x} q'$; in each case, the markings q and q' coincide except that $q'(x^o) = q(x^o) - 1$.

As the formula $\phi(Q)$ depends on the stable states $q \in Q$, we first deduce whether node Q contains any stable state.

Lemma 26. *A node Q of $BSD_b(N)$ contains a stable state iff 1,2-DFS starting from Q encounters a 1,2-node.*

So far, we considered nodes Q that contain a stable state. If node Q does not contain a stable state, then $\phi(Q)$ is the empty conjunction which is equal to true. In this case, node Q has label 3.

Lemma 27. *Q does not contain a stable state iff $\phi(Q)$ is the empty conjunction iff $\phi(Q)$ is true. If these three statements hold, then Q has label 3.*

For nodes without a stable state, we know by Lemmata 26 and 27 how to translate label and formula into each other, and we can *assume for the following* that $\phi(Q)$ has a conjunct. Q can have label 1, 2, or 3; the next two lemmata characterize the nodes with label 1 and 2, respectively.

By definition of formula $\phi(Q)$, all conjuncts have those inputs a of N as literals such that there is an a -labeled edge leaving Q . We factor out the disjunction of these inputs from $\phi(Q)$, and it remains to construct the remaining disjunct which is a CNF C . If this *remaining CNF* C has a conjunct false, then C is equivalent to false and we can reconstruct $\phi(Q)$ from the edges leaving Q . In this case, Q is labeled 1.

Lemma 28. *The remaining CNF C of some node Q has a conjunct false iff Q is labeled 1.*

We are left with considering nodes that are not labeled 1 and whose remaining CNF C is not equivalent to false. For such nodes, we determine whether there is some conjunct containing a literal *final*.

Lemma 29. *Assuming that node Q is not labeled 1, the remaining CNF C of Q has a conjunct containing *final* iff Q is labeled 2. Then the respective conjunct equals the literal *final*.*

Finally, we determine the remaining conjuncts for which it suffices to find at least the minimal ones regarding each conjunct as the set of its literals. These are sets of edge labels of the maximal paths being constructed during the 1,2-DFS.

Lemma 30. *Let C be the remaining CNF of a node Q . The sets of edge labels of the maximal paths being constructed during 1,2-DFS are conjuncts of C . Each conjunct of C that is not false or equal to *final* contains the set of edge labels of some maximal path constructed during 1,2-DFS.*

5.2 Deriving *bsd*-Semantics from Operating Guidelines

The previous results also show how to derive $BSD_b(N)$ from $OG_b(N)$; we collect the respective observations. First, we add the 0-labeled node U , as previously described, and we remove the empty node. For the other nodes, we run through our preceding considerations for constructing ϕ .

If $\phi(Q)$ is true, then there is no stable state $q \in Q$ and the label of Q is, therefore, 3 (see Lemma 27).

Otherwise, if $\phi(Q)$ is equivalent to the disjunction of those inputs a of N such that there is an a -labeled edge leaving Q , then the remaining CNF is false and the label of Q is 1 (see Lemma 28).

Otherwise, the remaining CNF C is not equal to false and we have to check whether *final* is a conjunct of C . By Lemma 29, this is the case if and only if the label of Q is 2. (To check semantically whether *final* is a conjunct without relying on the precise form of ϕ of C , we assign true to all outputs of N and false to all inputs and to *final*.) Then $\phi(Q)$ evaluates to false if and only if *final* is a conjunct. To all remaining nodes we assign label 3.

5.3 Accordance Check with Operating Guidelines

For open nets $Spec$ and $Impl$, with operating guidelines $OG_b(Spec)$ and $OG_b(Impl)$, we have that $Impl \sqsubseteq_{acc,b} Spec$ if and only if there exists a minimal simulation ϱ of $OG_b(Spec)$ by $OG_b(Impl)$ and, for each pair of nodes $(Q, Q') \in \varrho$, $\phi(Q)$ implies $\phi(Q')$ is a tautology [15].

Interestingly, this check shows that the simulation relation is the other way around compared to the *bsd*-setting. Checking b -accordance involves repeated checks of implications between the annotations, whereas in the *bsd*-setting (see Theorem 25), we simply compare numbers 0, 1, 2, 3 in constant time.

6 Conclusions

We presented a novel semantics for open nets assuming the absence of deadlocks as a minimal correctness criterion. The semantics consists of four sets of traces.

The set $bd_b(N)$ collects catastrophic traces due to bound violation; these traces modify all components just as divergence traces in failures semantics [2]. The sets $stop_b(N)$ and $dead_b(N)$ are successful and unsuccessful completed traces; because we are in an asynchronous setting, they can be continued with inputs; that is, they are quiescent as in I/O automata [10]. The fourth component, L_b , is just the language of the net N , comprising all traces.

We proved that our semantics can be translated back and forth into operating guidelines, and we derived the bsd -refinement relation from it, which coincides with (a slight modification of the) accordance relation. In addition, we proved bsd -refinement to be a fully abstract precongruence.

The bsd -semantics is related to the recently proposed notion of a reduced operating guideline [9]. The idea is to distinguish three disjoint subsets of nodes in an operating guideline such that the Boolean formulae can be derived from this information. The argumentation that leads to this representation has similarities to our arguments for translating $OG_b(N)$ into $BSD_b(N)$. However, in [9] responsiveness is considered: in addition to deadlock freedom, a b -controller in [9] also has to guarantee that in each state of the composition either a final state can be reached or a message is exchanged.

Different precongruences for asynchronously communicating processes have been studied. The introduced bsd -refinement is closely related to previous work of Vogler [16], closest to P-deadlock refinement. As a difference, in the setting of Vogler [16], the interface is not separated into input and output places, interface places may be unbounded (like in the sd -semantics), and the notion of a deadlock ignores τ -loops: a marking m is a deadlock if $m \xRightarrow{w}$ implies $w = \epsilon$. This leads to a much more complicated characterization.

Testing equivalence for asynchronous CCS is considered in [1], but it is an asymmetric notion focusing on the controller (i.e., the test) and not on the service; in contrast, the defining condition in Definitions 7 and 15 is symmetric in C and N . Avoidance of deadlocks is not so essential, and in fact τ -loops are not helpful or even a catastrophe; a process may receive the messages it has sent.

Stuck-free conformance [6] is a precongruence that excludes deadlocks. In contrast to bsd -refinement, it is based on a variation of failures semantics rather than traces. In [6], it has been proved that stable failures refinement [2] does not imply stuck-free conformance. In contrast, it has already been argued in a shared-variable setting in [4], that refusal sets are not needed when working with asynchronous communication.

In the area of SOC, the subcontract preorder [7] is an asymmetric notion also focusing on the tests. It is based on synchronous communication and only requires that the controller never gets stuck. In [7], it has been proved that the subcontract preorder coincides with must-testing [5] — that is, with stable failures refinement (for finitely branching processes without divergences).

Our goal was to provide a trace-based view on operating guidelines. In ongoing work, we investigate how the bsd -semantics of a service S can be used to check whether a service is a controller of S . In addition, we want to gain a better understanding which transformations bsd -refine a service, because these

transformations allow us to construct replaceable services. We will further study how our semantics needs to be adjusted if we consider responsiveness [9] rather than deadlock freedom. Here, we are particularly interested in the relation of the resulting semantics and the notion of a reduced operating guideline [9].

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