Instance Migration Validity for Dynamic Evolution of Data-Aware Processes

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Abstract—Likely more than many other software artifacts, business processes constantly evolve to adapt to ever changing application requirements. To enable dynamic process evolution, where changes are applied to in-flight processes, running process instances have to be migrated. On the one hand, as many instances as possible should be migrated to the changed process. On the other hand, the validity to migrate an instance should be guaranteed to avoid introducing dynamic change bugs after migration. As our theoretical results show, when the state of variables is taken into account, migration validity of data-aware process instances is undecidable. Based on the trace of an instance, existing approaches leverage trace replaying to check migration validity. However, they err on the side of caution, not identifying many instances as potentially safe to migrate. We present a more relaxed migration validity checking approach based on the dependence graph of a trace. We evaluate effectiveness and efficiency of our approach experimentally showing that it allows for more instances to safely migrate than for existing approaches and that it scales in the number of instances checked.

Index Terms—Data-aware process, dynamic evolution, instance migration, migration validity, trace slicing

1 Introduction

PRocesses are widely used in inter-organizational applications in networked environments, e.g., in business process management [1], [2] and service compositions [3], [4], [5], scientific and cloud workflows [6], [7], [8], Web applications and Internetware [9], [10], [11], to name a few. Since networked environments are open, dynamic, and uncontrolled [12], [10], [9], processes must often evolve to adapt to new business requirements, strategies, and changing customer needs. Process evolution may also result from fixing bugs and from process enhancements [13]. It is considered a key challenge to handle in-flight process instances when a process is updated from its current version to a new version [14], [15], [16], [17], [18]. Below, we often refer to the *old* and the *new* versions of the process; the new process version results from changes applied to the old one.

A naive strategy is to withdraw the running instances and restart them from scratch according to the new process version. Despite its simplicity, this strategy may be inapplicable in practice for several reasons. First, this strategy is not an option for handling migration of mission-critical processes (e.g., an online auction service, real-time monitoring) [19]. Otherwise, severe or unacceptable consequences may ensue. Also, the inefficiency of this strategy may not be acceptable even for ordinary business processes and applications [20]. For example, if a process instance is in an non-compensable state [21], it might be infeasible to restart the instance. Finally, it is both time-consuming and cost-ineffective to restart a running instance according to the new version, particularly when the process is long-running [15].

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A more promising strategy is to migrate running instances dynamically to the new process version. This mechanism is referred to as instance migration [14], [15], [16]. The crux of instance migration is to ensure *migration validity*, that is, to determine whether there is a state in the new process version that is consistent with the current state of the instance in the old version [15], [22]. Provided that migration validity is met, after the instance migrates to the new version, it behaves as if it had been executing according to the new version from the respective state.

Since executable processes involve control flow, data (variables), time-related properties, environmental properties, and access control policies, all these elements should be considered for instance migration. However, control flow and data (variables) are the most fundamental elements [23], [24], [25], [26], [27]. Therefore, in this work, we focus on instance migration validity of data-aware processes [23], [24], [27], where besides control flow, variables read and written are indispensable for migration validity checking. Specifically, variable state (i.e. the current value of a process variable at the migration time) needs consideration in the instance state. Unfortunately, as we establish in this paper, it is generally undecidable to check migration validity when variable state is taken into account. We elaborate on this result in Section 4.1. Undecidability implies that it is impossible to find a computable sufficient and necessary condition to check instance migration validity. As a consequence, the only option we have is to find sufficient conditions to tackle this problem. The sufficient conditions can be used as the migration criteria. Note that the updated process version is assumed to be sound (i.e., it is free of errors such as deadlocks, livelocks, etc.) [28]. Thus, if an instance satisfies the migration criterion, its migration does not introduce dynamic change bugs [15], [16], because the subsequent behaviour of the migrated instance is just similar to the behaviour of a process instance of the new version.

In practice, it is desirable to migrate as many running instances to the new process version as possible. The reasons are two-fold. First, this allows migrated instances to benefit from the advantages and opportunities of process evolution. Second, this lightens the burden of maintenance from the perspective of process holders (process management systems) [15]. Specifically, if more instances are migrated, the old process version can be unmaintained in a short time so that subsequent changes can only be applied to the latest version. Nevertheless, it is challenging to find a migration criterion that is as relaxed as possible (i.e., allows to safely migrate as many instances as possible.) Most existing approaches simplify this problem by merely focusing on control-flow state of the running instance while variable state is not taken into account [14], [15], [17], [29], [30], [31]. Due to neglecting to consider variable state, these approaches may lead to both false negatives (i.e., reject instances as invalid, while, in essence, they could have been safely migrated) and false positives (i.e., allow instances to be migrated, whereas, in essence, the migrations are not valid) for migration validity checking. Although some work realizes the necessity of considering the variable state in migration validity checking [32], to the best of our knowledge, few approaches adopt variable state in the definition of migration validity, and no solution is known to us that checks whether a process instance ensures variable consistency before and after migration.

Our goal is to determine a more relaxed migration criterion such that migration validity is ensured, on the one hand, and more process instances can migrate to the new process version, on the other hand. To this end, in our previous preliminary study [22], we took into account both control-flow state and variable state in the instance state, and proposed a novel migration criterion based on the instance dependence graph of the process instance trace. This paper extends our previous work [22] and makes the following contributions:

1) We formulate the concept of migration validity by taking variable state into account. Based on this, we prove that it is generally an undecidable problem to check migration validity. We also discuss the subcase of the problem that is decidable and specify the associated complexity.
2) We present a systematic solution of our approach, including a comprehensive description of our relaxed migration criterion, correctness proofs of both the traditional trace replaying and our approach, detailed algorithms of our approach to migration validity checking, and time complexity analysis of the proposed algorithms.
3) We realize our approach in a proof-of-concept tool Dilepis whose input consists of the old and the new data-aware processes specified in WS-BPEL [33] (i.e., the de facto standard for service-oriented executable processes), and traces in the XES format [34] (i.e., the de facto standard for event logs in the domain of process mining).
4) We evaluate the effectiveness and the efficiency of our approach by applying it and other approaches that are based on trace replaying to semi-synthetic data sets derived from real-world data-aware processes. We also present a case study to compare different approaches. The evaluation results demonstrate that our approach (i.e., the migration criterion) is more relaxed than existing ones and that it scales well in practice.

The remainder of the paper is organized as follows. Section 2 reviews related work. In Section 3, we first introduce some background material and provide a running example to motivate our work. In Section 4, we present our approach to migration validity checking of running process instances. In Section 5, we present the design of our implemented research prototype. In Section 6, we conduct experimental evaluation to investigate the effectiveness and the efficiency of our approach. In Section 7, we discuss the merit and complements of our approach. Section 8 concludes the paper and envisions future work.

2 Related Work

In this section, we review related work on instance migration for dynamic process evolution. Existing approaches fall into two major categories. The first kind defines the migration criteria from the perspective of process structures before and after change, while the second kind defines the criteria based on execution traces (i.e., completed activity sequences) of running instances. Many existing approaches focus on control-flow state consistency to ensure migration validity, while variable state consistency is not fully taken into account.

Let us first review representative work of the first kind. In [15], Aalst and Basten provide transfer rules to map a state of the old process version to a consistent state of the new version. These rules can guarantee proper termination of the migrated instances from the control-flow perspective. The approach requires that the two process versions are in an *inheritance* relation. Liske *et al.* present in [29] a similar approach which relaxes the inheritance relation to the *accordance* relation, i.e., the new process version should preserve all compatible partners of the old version. In addition, Aalst proposes another approach without restricting the change types to the control-flow of processes [35]. The approach compares the old and new process versions to obtain so-called change regions. Once an instance is not in the change region, it is permitted to migrate.

Next, we turn to representative approaches of the second kind. In the project WIDE [14], Casati *et al.* present an instance migration criterion called *trace replaying*: If the trace of a running instance can be replayed in the new process version, it is allowed to migrate [14], [36]. It is worth mentioning that trace replaying is only proposed to guarantee instance migration validity from the control-flow perspective. In the project ADEPT [37], [32], [18], Rinderle-Ma and Reichert put forward a migration criterion based on the pruned traces of the running instances. A pruned trace is derived from the original trace by first deleting activities which are not contained in the new process, and then discarding the activity occurrences related to loop iterations other than the last one. In this approach, a running instance can migrate if its pruned trace can be replayed in the new process version. However, as the authors point out, their approach can only guarantee the correctness of the migrated instances from the control-flow perspective [32]. When variable state is taken into account, the approach is still conservative and the migration criteria are not relaxed enough.

Ryu *et al.* [17] establish that a running instance can be migrated to the new process version if both *backward compatibility* and *forward compatibility* are met. Backward compatibility is just like the criterion of trace replaying. Forward compatibility requires that the new version should preserve traces of the old version. In our opinion, forward compatibility is not necessary in general evolution cases. Zeng *et al.* [30] propose an instance migration criterion which relaxes the traditional trace replaying criterion. Unfortunately, this criterion is only applicable to processes without loops.

To summarize, most existing approaches only consider control-flow state, and thus may produce false positives and false negatives when employed to check instance migration validity of data-aware processes. Our approach belongs to the second kind. Different from existing approaches, our approach takes into consideration both control-flow state and variable state for migration validity checking. Moreover, our migration criterion is more relaxed than existing approaches based on trace replaying [14], [32].

Notably, the above-reviewed literature and our work, all focus on instance migration within a single-controlled process (orchestration), where changes are limited to the orchestration itself. When changes extend beyond the scope of an orchestration, environment properties such as partner orchestrations (services) should be considered [38], [39], [40], [41], [42]. This situation is referred to as choreography evolution [41]. Existing work concentrates on the problems of change propagation, change negotiation, and orchestration co-evolution [41], [43], [42], [44]. For a more detailed review of work on instance migration and work on process change (including choreography change), we refer to surveys on the subject [16], [27].

3 Background

In this section, we first introduce preliminaries necessary to understand our work; then we motivate our approach with a running example.

3.1 Preliminaries

In this paper, data-aware processes are used as an abstraction of executable business processes, e.g., WS-BPEL processes. We employ directed graphs to represent data-aware processes with the help of four structured activities, including XOR-split, XOR-join, AND-split, AND-join [45].

Definition 1 (**Data-aware process**). *A data-aware process is a five-tuple $P = (N, F, D, I, O)$:*

- *N is a union of a set of basic activities and a set of structured activities including XOR-split, XOR-join, AND-split, AND-join.*
- *F is a set of flow relations representing activity orders.*
- *D is a set of variables defined or used in P.*
- *I, O: $N \to 2^D$ are functions assigning input and output variables to each activity in N.*

It is assumed that a process has a unique start activity A_s and a unique exit activity A_e. The operational semantics of data-aware processes is described in our previous work [46]. A data-aware process P can execute and each execution corresponds to a process instance. If executed activities of an instance are recorded in the order of timestamps, a trace of P is obtained. In the rest of the paper, data-aware processes and processes are used interchangeably.

In data-aware processes, different activities may be interrelated by dependences, e.g., *control* and *data dependences*. Control and data dependences are well-established concepts in the domain of programming language and software engineering [47]. To make this paper self-contained, we review these concepts, defined in the context of business processes.

Definition 2 (**Post-dominance**). *In a data-aware process P, an activity A_i is post-dominated by another activity A_j if each directed path from A_i to the exit activity A_e (excluding A_i) contains A_j.*

Definition 3 (**Control dependence**). *In a data-aware process P, an activity A_j is control-dependent on another activity A_i if and only if there exists a directed path ρ from A_i to A_j with any activity A_k in ρ (excluding A_i and A_j) post-dominated by A_j and A_i is not post-dominated by A_j.*

If an activity A_j is control-dependent on another activity A_i, A_i is usually a conditional activity such as an XOR-split. Data dependences are classified into three categories: *true dependence*, *anti-dependence*, and *output dependence* (cf. Definition 4) [47], [48].

Definition 4 (**Data dependence**). *In a path ρ of a data-aware process P, an activity A_j is true-dependent (anti-dependent, or output-dependent) on another activity A_i iff*

- *There is a variable $v \in I(A_j) \cap O(A_i)$ ($O(A_j) \cap I(A_i)$, or $O(A_j) \cap O(A_i)$).*
- *In ρ, there is no A_k between A_i and A_j such that $v \in O(A_k)$.*

Assume A_i precedes A_j in a loop of a process P. A_i is true-dependent on A_j if the latter activity writes a process variable read by A_i. Definition 4 covers this case, and the dependence can be analyzed (cf. Algorithm 1 in Section 4.3.1).

Apart from control dependence and data dependence, another type activity dependence exists in WS-BPEL processes, i.e., the *asyn-invocation dependence* [49], which is caused by the asynchronous communication mechanism of WS-BPEL processes. Informally, a <receive> activity A_j is asyn-invocation dependent on a preceding one-way <invoke> activity A_i if and only if A_j is responsible for receiving the "response" (i.e., the invocation result) of A_i [49].

Table 1 summarizes the notations used in this paper.

3.2 A Running Example

In this section, we illustrate a dynamic evolution scenario of a data-aware process (WS-BPEL process) to motivate our work. The UML activity diagram depicted in Fig. 1a shows a WS-BPEL process of a Chinese tour agency that provides overseas travels, where the input and output of each activity are also depicted. The process works as follows. After receiving a tour query from a customer, it invokes the

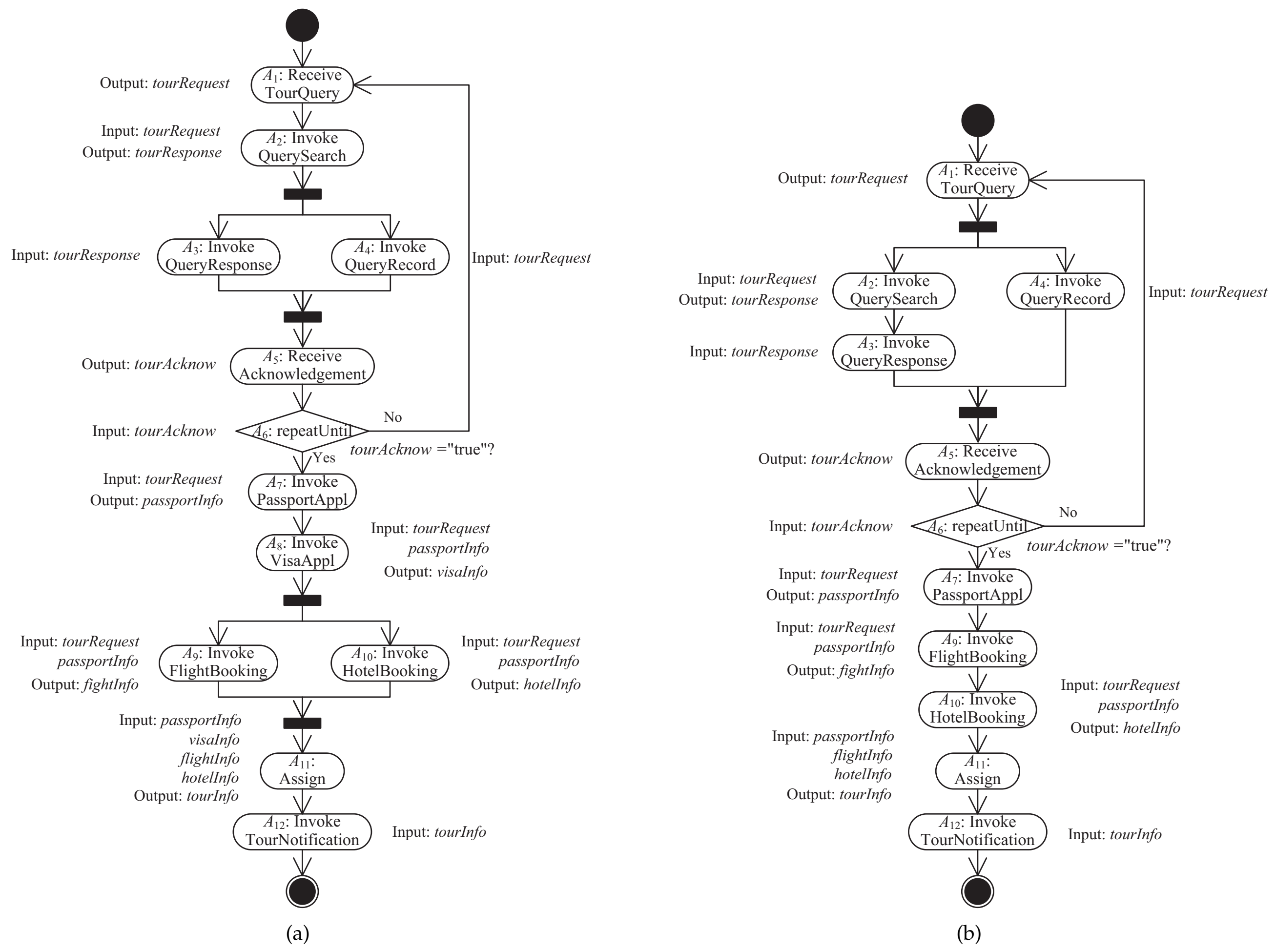


Fig. 1. A running example: (a) WS-BPEL process P_1 before evolution, (b) WS-BPEL process P_2 after evolution.

TABLE 1
Notations Used in the Paper

Notation	Description
$P = (N, F, D, I, O)$	A data-aware process P
(P, M)	Control-flow state M of process P
var_{A_i}	Variable var defined by activity A_i
$<A_i, A_j>$	An activity dependence from A_i to A_j
$IDG = <N, E>$	An instance dependence graph
$\|S\|$	The number of elements in set S
$S_1 \uparrow S_2$	Discarding S_1's elements not in S_2
$\sigma[i]$	The i^{th} activity in trace σ
f: $X \nrightarrow Y$	A partial function from X to Y
var_{A_i}	A variable var defined by activity A_i
$ReachingDefs(P, \sigma)$	Reaching definitions at the end of σ

query search service to obtain the response for the query. Then, it sends the response to the customer and meanwhile records the query. If the customer does not acknowledge (confirm) the tour, the process will go back to the first stage to wait for another query from the customer. Otherwise, it first invokes the passport service to apply for a passport for the customer. Based on the passport details and the customer's tour request, the process then invokes the visa service to apply for the visa needed by the customer. Next, it concurrently books the flight and hotel for the customer. After all these steps, it combines the results, which are finally sent back to the customer. In 2014, Indonesia passed a new law, stating that from Jan 1st, 2015, Chinese tourists can travel to Indonesia without a visa. In the meantime, the tour agency finds that it can record the query in parallel with the query search followed by the response to the customer. In addition, it also find that most of the hotel services have QoS (i.e., cost) correlations with the flight services [50], [51]. For example, if a client selects Lion Air, she will enjoy a discount when booking certain hotels in Indonesia. For these reasons, the Chinese tour agency modifies its WS-BPEL process for clients who plan to visit Indonesia. The modified process is depicted in Fig. 1b.

We refer to the WS-BPEL processes in Fig. 1a and 1b as P_1 and P_2. Suppose that there is an instance I of P_1. Its current state and trace (completed activity sequence) are s and $\sigma = A_1A_2A_3A_4A_5A_6A_1A_2A_4A_3A_5A_6A_7A_8A_{10}A_9$, respectively. Since the WS-BPEL process is long-running, it is preferable to utilize the mechanism of instance migration to cope with dynamic evolution. The central question here is how to justify whether the migration of I from P_1 to P_2 is valid or not.

To make existing approaches applicable in this scenario, an activity A_i in a trace σ can be replayed in a state s' of a process (e.g., P_2) if A_i can be executed in s' and its input and output should be consistent with those in P_2. Under this improvement, let us investigate whether existing approaches are applicable to address this problem. If the migration criterion based on the traditional trace replaying is used [14], I will fail to be migrated because σ cannot be replayed in P_2. If the migration criterion based on the relaxed trace replaying [32] is used, I will also fail to be migrated because the reduced trace $\sigma' = A_1A_2A_4A_3A_5A_6A_7A_8A_{10}A_9$ of σ still cannot be replayed in P_2. On the other hand, the projection of I's state s onto P_2 corresponds to a reachable state of P_2. Consequently, in fact, the migration of I from P_1 to P_2 is valid. This suggests that existing migration criteria are still overly conservative. Below in Section 4.3, we present a more relaxed migration criterion.

4 Approach

In this section, we first reformulate the notion of migration validity and then present our approach to instance migration validity checking.

4.1 Migration Validity

Since most existing migration validity criteria merely focus on control-flow state, they are not directly applicable to support the dynamic evolution of data-aware processes. In the following, we first reformulate migration validity checking by considering both control-flow state and variable state. Then, we draw an important conclusion for migration validity checking of process instances.

A running instance is characterized by the process definition according to which the instance executes and its runtime state. Informally, the instance state is a characterization of all variables of the instance, more formally defined next.

Definition 5 (Instance state). *A state s of an instance of process P is defined as a partial function which maps variables in P to values in the respective ranges (codomain), i.e., s: $D \nrightarrow R$, where D and R are the sets of variables (including a virtual variable called PC which points to the current control-flow state) of P and their ranges, respectively.*

The virtual variable PC is explained as follows. It always points to the current control-flow state which specifies the next activity (activities) to be executed. That is, $s(PC) = \{A_i | A_i \text{ is enabled}\}$, where the condition "$A_i$ is enabled" denotes that A_i can be executed next. If Petri nets [52] are employed to represent the control flow of processes, a marking M of the Petri net denotes a control-flow state of the process. For simplicity, we can use $s(PC) = M$ to replace $s(PC) = \{A_i | A_i \text{ is enabled}\}$.

Typically, an instance begins in an initial state with initial values assigned to some variables (i.e., input) in D. Its state changes during the execution of the instance. A state s is said to be a reachable state of a process if and only if there is an instance which can reach s at some time in the future from its initial state. The reason why s is defined as a partial function is that some variables in D have not been assigned values in s, and certain variables will never be assigned values even when the instance completes, for example, if the process involves alternative structures. Under control of the process engine, an instance can suspend its execution in state s (at time t_1) and can resume execution from the suspended state s at a later time t_2.

When the dynamic evolution of a process occurs, we need to substitute the new version $P_2 = (N_2, F_2, D_2, I_2, O_2)$ for the old version $P_1 = (N_1, F_1, D_1, I_1, O_1)$, while there is one or more instance of P_1 still running. It is assumed that both P_1 and P_2 are "sound" processes in the sense that they can execute properly and produce the expected results [28]. The principal problem here is whether or not an instance of P_1 can migrate from P_1 to P_2 such that it can go on with its execution according to P_2. To this end, we need to explicitly specify the expected execution behaviour of an instance after migration. In general, the behaviour of an instance which undergoes a change is not the same as the behaviour of an instance of either P_1 or P_2. The best we can hope for is that after the change, the subsequent behaviour of the migrated instance is like that of an instance of P_2.

We find that two different instances I_1 and I_2 of P_2 can reach the same state s from the same initial state but with different execution histories (i.e., traces). We note that their subsequent executions from s may be identical, that is, we cannot differentiate them according to their subsequent behaviour. This indicates that if a suspended instance I_3 of P_1 resumes its execution from state s following P_2, we can neither differentiate I_3 from I_1 nor from I_2 based on their subsequent executions. Moreover, I_3 will not get stuck, because I_1 and I_2 never get stuck either, which is ensured by the soundness of P_2 [28]. Bearing this in mind, we define instance migration validity as follows.

Definition 6 (Migration validity). *A migration of a running instance I from the old process version $P_1 = (N_1, F_1, D_1, I_1, O_1)$ to a new version $P_2 = (N_2, F_2, D_2, I_2, O_2)$ is valid if there is a partial function S: $s \nrightarrow s'$ which maps I's current state s in P_1 to a reachable state s' in P_2. The state s' is called the target state for the migration.*

There is no restriction on the changes from P_1 to P_2. The changes can involve activity/variable deletion, activity/variable addition, activity/variable substitution, activity reordering, variable type modification, activities' input/output changes, etc. Notably, if an activity of P_1 is preserved in P_2, its input and output should remain the same (at least type-compatible); otherwise, the updated activity is regarded as a new activity in P_2, even if its name remains the same.

Theoretically, the partial function S for the state mapping can be arbitrary. To simplify the problem, S is defined as follows. For any non-virtual variable $var \in D_1$ that has been assigned a value in s, if $var \in D_2$, $(S(s))(var) = s(var)$ (i.e., $S(var, *) = (var, *)$, where $*$ is the value of var in P_1); otherwise, $S(var, *)$ is undefined, because there is no variable in $V(P_2)$ that corresponds to var. For the virtual variable PC in P_1, its value cannot be directly copied to that in P_2, because the activities which PC points to in P_1 could be removed from P_2 or moved to another place in P_2, or new activities could be inserted before them in P_2. Thus, the control-flow state mapping needs to be defined additionally. The state mapping between non-virtual variables may need the help of programmers. For example, if a variable a in P_1

is renamed to b in P_2, only the programmers who maintain the process are aware of this substitution. To define state mapping without the help of programmers, we assume that when a process evolves from P_1 to P_2, activity/variable renaming without substantial change is not considered. Unless otherwise stated, the partial function S for state mapping defined above is used in the remainder of this paper.

Example 1 (Continuation of the running example from Section 3.2)**.** *For the instance I whose trace and current state are $\sigma = A_1A_2A_3A_4A_5A_6A_1A_2A_4A_3A_5A_6A_7A_8A_{10}A_9$ and s, respectively, we check whether the migration of I from P_1 to P_2 is valid. If control-flow state is mapped in the same way as non-virtual variables, a state mapping S is obtained such that $S(s) = s' = \{PC = \{A_{11}\}$, tourRequest = $*$, tourResponse = $**$, tourAcknow = $***$, passportInfo = $****$, flightInfo = $*****$, hotelInfo = $******\}$, where $*$ to $******$ represent the values of corresponding variables. Since s' is a reachable state of an instance (say, I' whose trace is $A_1A_2A_4A_3A_5A_6A_7A_9A_{10}$) of P_2, the migration of I from P_1 to P_2 is valid and s' is the target state.*

Although Example 1 is straightforward, in the general case, unfortunately, the problem of migration validity checking is undecidable. To this end, we first show that determining whether a given state s is reachable in a process can be reduced to the *halting problem* [53]. The halting problem is to determine whether a given program will eventually halt on a given input, which is well-known to be undecidable.

Lemma 1. *Given an arbitrary data-aware process P, with initial state s_0, determined by the given input, it is undecidable to check whether or not a given state s is reachable from s_0.*

Proof. Let us construct a process P. It first executes an arbitrary process P'. Then, if P' terminates in a state s, P copies the current variable values in s to the corresponding variables of P. As a consequence, P' would halt when executed from the initial state s_0 if and only if state s is reachable in P. However, it is undecidable whether a program (e.g., a data-aware process) ever halts when executed from its initial state. Hence, it is also undecidable to determine whether a given state can be reached in a process. □

Since data-aware processes (e.g., WS-BPEL processes) are provided with all features of the programming model used in [54], Lemma 1 can be seen as an extension of the result presented in [54] which states that the reachability of the final state of a program is in general undecidable. With Lemma 1, we can prove the undecidability of checking the migration validity of a process instance.

Theorem 1. *Given two process versions P_1 and P_2, a partial function S for state mapping, and an instance I of P_1 whose current state is s, it is undecidable whether the migration of I at s from P_1 to P_2 via the state mapping S is valid.*

Proof. To check the migration validity of I, according to Definition 6, we need to determine whether $S(s)$ can be reached from the initial state of P_2 (we assume that P_1 and P_1 share the same input and thus the same initial state). Lemma 1 ensures the undecidability of this problem. Hence, Theorem 1 holds. □

Theorem 1 implies that we cannot find a sufficient and necessary condition for determining migration validity. The best we can do is to find a more relaxed sufficient condition to address the problem. Generally speaking, since the undecidability of the problem is caused by a possibly infinite number of reachable states of the new process P_2, in theory, the problem becomes decidable when P_2 involves a bounded number of states reachable from its initial state s_0. However, even in that case, the number of reachable states in P_2 grows exponentially with the number of activities concurrently executing, and thereby it is still intractable to determine whether the migration of an instance is valid.

4.2 Trace Replaying Revisited

The approach of trace replaying is commonly used for migration validity checking from the control-flow perspective. Given the trace σ of a running instance I of the old process version P_1, if σ can be replayed in the new process version P_2, i.e., σ is also a trace of P_2, then I is allowed to migrate from P_1 to P_2. Otherwise, it is not permitted to migrate. In this paper, we improve trace replaying by requiring that, in addition to the replayed trace σ, for each activity $A_i \in \sigma$, the input and output variables of A_i in P_1 should be consistent with those in P_2. With this improvement, we show that, trace replaying also ensures migration validity (cf. Definition 6) from the data perspective.

Definition 7 (**Reaching definitions**)**.** *Reaching definitions at a given activity A_i in a trace σ are a set of variables (defined by earlier activities in σ) which can reach A_i without intervening redefinitions.*

Given a trace σ of a process P, we use $ReachingDefs(P, \sigma)$ to represent the reaching definitions (i.e., variables that have been assigned values) at the end of σ.

Theorem 2. *Given two process versions $P_1 = (N_1, F_1, D_1, I_1, O_1)$, $P_2 = (N_2, F_2, D_2, I_2, O_2)$, and an instance I of P_1 whose current state and completed trace are s and σ, respectively, if σ can be replayed in P_2, the migration of I from P_1 to P_2 is valid.*

Proof. Suppose that s' is the state obtained after all activities in σ have been replayed in P_2, starting from its initial state. $ReachingDefs(P_1, \sigma)$ and $ReachingDefs(P_2, \sigma)$ summarize variables in D_1 and D_2 that have been assigned values in state s and s', respectively. Since σ is a trace of both P_1 and P_2, it follows that $ReachingDefs(P_2, \sigma) = ReachingDefs(P_1, \sigma)$ and for any variable $v \in ReachingDefs(P_2, \sigma) \cap ReachingDefs(P_1, \sigma)$, $s(v) = s'(v)$. Therefore, (I) for each variable $v \in ReachingDefs(P_1, \sigma) \cap ReachingDefs(P_2, \sigma)$, we have $(S(s))(v) = s(v) = s'(v)$; (II) for each variable $u \in (D_1 \cap D_2) \setminus ReachingDefs(P_2, \sigma)$, $s(u)$ and $s'(u)$ are both undefined, thus $(S(s))(u)$ as well; (III) for each variable $w \in D_2 \setminus D_1$, $s'(w)$ is undefined since no activity of P_2 in σ can assign value to w. (IV) Let $S(PC, M_1) = (PC, M_2)$, where M_1 and M_2 are control-flow states obtained after σ is replayed in P_1 and P_2, respectively. Altogether, $S(s) = s'$. According to Definition 6, the migration of I from P_1 to P_2 is valid and s' is the target state in P_2 for the migration. □

Example 2 (Continuation of the running example from Section 3.2)**.** *Assume that there is an instance I_1 of P_1. Its trace*

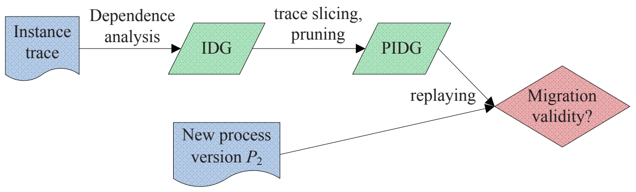


Fig. 2. Framework of our approach.

is $\sigma_1 = A_1A_2A_4A_3A_5A_6A_7$ and its current state and control-flow state are s and $M_1 = \{A_8\}$, respectively. Since σ_1 can be replayed in P_2, the migration of I_1 from P_1 to P_2 is valid. Let $S(PC, M_1) = (PC, M_2)$, where $M_2 = \{A_9\}$ is the control-flow state reached after σ_1 is replayed in P_2. The state mapping of non-virtual variables are defined as before. $S(s)$ is the target state for I_1's migration. Therefore, after migration, I_1 can resume execution from activity A_9 in P_2.

4.3 Migration Validity Checking

The approach of trace replaying is conservative because it is too rigid in requiring that activity occurrences in a trace σ to also complete in the same order in the new version P_2. Our observation is that there is no need to require activity occurrences with no direct or indirect dependences to follow the order set by σ. Instead, they can be replayed concurrently, i.e., their replay can be in any order. From this, we can obtain a more relaxed migration criterion (cf. Theorem 3), and our approach to migration validity checking involves the following three steps (cf. Fig. 2):

1) **Constructing the instance dependence graph**. We capture the activity dependences of σ into an instance dependence graph (IDG). We also summarize the reaching definitions at the end of σ into a set $ReachingDefs(P_1, \sigma)$, where P_1 represents the old process version.
2) **Deriving the pruned instance dependence graph**. For every variable $var \in ReachingDefs(P_1, \sigma) \uparrow D_2$, we exploit a backward slicing technique to obtain the activity occurrences (trace slice) which have direct or indirect impact on var. If an activity occurrence in σ is not contained in any such trace slice, this activity occurrence and the edges associated with it are removed from the IDG, thus obtaining a pruned instance dependence graph (PIDG).
3) **Checking migration validity**. We show that if there exists a topological sort of the activity occurrences in the PIDG such that it can be replayed in the new process version P_2, the instance migration is valid.

4.3.1 *Constructing Instance Dependence Graph*

Before elaborating on Step 1 of our approach, we first present the definition of the IDG.

Definition 8 (Instance dependence graph, IDG). *An instance dependence graph of a trace σ is a directed graph IDG = $<N, E>$, where*

- *N is a node set which represents activity occurrences in σ.*
- *$E \subseteq N \times N$ is a set of directed edges. An edge $<A_i, A_j> \in E$ denotes a control dependence or a data dependence from activity occurrence A_i to activity occurrence A_j.*

Due to loops, some activities may occur more than once in trace σ. According to the definition of the IDG, different occurrences of the same activity are represented by different nodes instead of the same node. Therefore, a node (activity occurrence) in the IDG cannot be dependent on an activity occurrence after it in σ. That is, the IDG is a directed acyclic graph (DAG) by nature. If not stated otherwise, activities and activity occurrences are used interchangeably in the rest of the paper. Note that data dependences can be directly obtained from the trace. However, if structured activities, like an XOR-join, are not recorded in the trace, it is difficult to determine the control dependences. Hence, control dependences in a trace are determined from the original process. When the IDG of a trace σ is constructed, the reaching definitions at the end of σ can be obtained as well.

Let P_1 be a data-aware process and S_{CD} be the set of control dependences between activities in P_1. If σ is a trace of an instance of P_1, then Algorithm 1 is provided to construct the instance dependence graph $IDG(N, E)$ of σ and to obtain the dynamic reaching definitions $ReachingDefs(P_1, \sigma)$ at the end of σ. More specifically, Line 5 inserts a new node into the IDG for each activity in σ. For the new node, Lines 6-8 add edges of control dependence into the IDG; Lines 9-11 add data dependence edges with the current node as the target into the IDG; Lines 12-17 update the dynamic reaching definitions. When the outer "for" loop terminates, we obtain the IDG of σ. The dynamic reaching definitions at the end of σ, i.e., $ReachingDefs(P_1, \sigma)$, is also stored in the output $Defs$.

Algorithm 1 Construct the instance dependence graph

```
Input: the trace $\sigma$ of a running instance of the old process
    version $P_1$; the set of control dependences $S_{CD}$ in $P_1$
Output: the instance dependence graph $IDG(N, E)$ of $\sigma$; the
    reaching definitions $ReachingDefs(P_1, \sigma)$ at the end of $\sigma$
1:  $IDG(N, E) \leftarrow \emptyset$
2:  $Defs \leftarrow \emptyset$
3:  $Uses \leftarrow \emptyset$
4:  for $j \leftarrow 1$ to $|\sigma|$ do
5:      $N \leftarrow N \cup \{\sigma[j]\}$
6:      for each $\sigma[i] \in N$ do
7:          if $<\sigma[i], \sigma[j]> \in S_{CD} \wedge \nexists k$: $i<k<j$, $\sigma[k]=\sigma[i]$ then
8:              $E \leftarrow E \cup \{<\sigma[i], \sigma[j]>\}$
9:      for each $var \in inPut(\sigma[j])$ do
10:         $E \leftarrow E \cup \{<\sigma[k], \sigma[j]>|\ var_{\sigma[k]} \in Defs\}$
11:         $Uses \leftarrow Uses \cup \{var_{\sigma[j]}\}$
12:     $Def(\sigma[j]) \leftarrow \emptyset$
13:     $Kill(\sigma[j]) \leftarrow \emptyset$
14:     for each $var \in outPut(\sigma[j])$ do
15:         $Def(\sigma[j]) \leftarrow Def(\sigma[j]) \cup \{var_{\sigma[j]}\}$
16:         $Kill(\sigma[j]) \leftarrow Kill(\sigma[j]) \cup \{var_{\sigma[i]}|\ var_{\sigma[i]} \in Defs\}$
17:     $Defs \leftarrow (Defs \setminus Kill(\sigma[j])) \cup Def(\sigma[j])$
18: return $(IDG(N, E), Defs)$
```

Example 3 (Continuation of Example 1)**.** *With Algorithm 1, we obtain the IDG (cf. Fig. 3) of instance I whose trace is $\sigma = A_1A_2A_3A_4A_5A_6A_1A_2A_4A_3A_5A_6A_7A_8A_{10}A_9$. There*

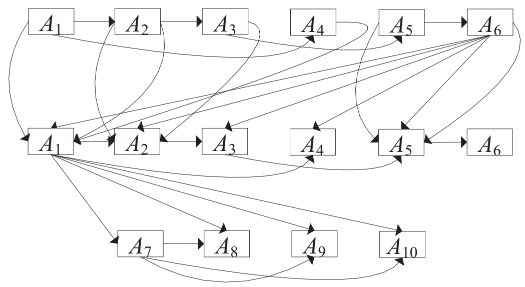


Fig. 3. IDG of $\sigma = A_1A_2A_3A_5A_4$.

is an asyn-invocation dependence from A_3 to A_5 [49]; there are control dependences from the first occurrence of A_6 to the second occurrences of A_1-A_5, because the first occurrence of A_6 determines the execution of A_1-A_5 (the second occurrences); other edges are all data dependences. It can be seen that the IDG is a DAG, though the process P_1 involves a loop (cf. Fig. 1). The reaching definitions at the end of σ is $ReachingDefs(P_1, \sigma) = \{tourRequest_{A_1}, tourResponse_{A_2}, tourAcknow_{A_5}, passportInfo_{A_7}, visaInfo_{A_8}, flightInfo_{A_9}, hotelInfo_{A_{10}}\}$, where var_{A_i} represents that the variable var is defined by activity A_i.

4.3.2 Deriving Pruned Instance Dependence Graph

The aim of Step 2 of our approach is to remove from the IDG those activities that do not affect the state mapping of the instance. To this end, we define a trace slice as follows.

Definition 9 (**Trace slice**). *A trace slice of a trace σ with respect to a variable (i.e., reaching definitions) v at a given activity A_i in σ is a set of activities that have direct and indirect impact on the value of v, which is denoted as $TS(\sigma, v)$.*

The trace slice is acquired from the IDG of the trace. We obtain the trace slice with respect to a variable $v \in ReachingDefs(P_1, \sigma) \uparrow D_2$ by first finding the activity A_i that lastly defines v in σ and, then, using a backward slicing approach, to find all activities in the IDG that are reachable to A_i, i.e., the activities on which A_i is directly and transitively dependent.

We note that only trace slices with respect to variables in $ReachingDefs(P_1, \sigma) \uparrow D_2$ are relevant to the state mapping. If an activity A_i in σ is not involved in any such trace slices, we draw the conclusion that A_i exerts no impact on the variables in D_2, and, thus, there is no need to replay A_i in the new process version P_2. Once we remove all such activities and their edges from the instance dependence graph, a pruned instance dependence graph (PIDG) can be obtained, which is also a DAG.

Algorithm 2 is presented to derive the PIDG from the corresponding IDG. Apart from the output of Algorithm 1, the input of Algorithm 2 also includes the variable set D_2 of the new process version P_2. Algorithm 2 proceeds as follows. For each variable $var_{\sigma[i]}$ in $ReachingDefs(P_1, \sigma) \uparrow D_2$, Line 4 determines the activity $\sigma[i]$ which defines the variable var. The loop (Lines 3-13) identifies the trace slice which has impact on the value of var at $\sigma[i]$. Line 4 and Line 12 add activities in the trace slice into the node set N' of the PIDG; Line 10 inserts the dependence edges between activities in the trace slice into the edge set E' of the PIDG. After the trace slices with respect to all variables in $ReachingDefs(P_1, \sigma) \uparrow D_2$ are found, the PIDG $PIDG(N', E')$ is obtained.

Algorithm 2 Derive the pruned instance dependence graph

```
Input: the instance dependence graph $IDG(N, E)$ of $\sigma$; the
    reaching definitions $ReachingDefs(P_1, \sigma)$ at the end of $\sigma$;
    the variable set $D_2$ of the new process version $P_2$
Output: the pruned instance dependence graph $PIDG(N', E')$
    of the instance trace $\sigma$
1: $PIDG(N', E') \leftarrow \emptyset$
2: $Defs \leftarrow ReachingDefs(P_1, \sigma) \uparrow D_2$
3: for each $var_{\sigma[i]} \in Defs$ do
4:     $N' \leftarrow N' \cup \{\sigma[i]\}$
5:     $traversalQueue.enqueue(\sigma[i])$
6:     while $traversalQueue \neq \emptyset$ do
7:         $\sigma[k] \leftarrow traversalQueue.dequeue()$
8:         for each $<\sigma[j], \sigma[k]> \in E$ do
9:             if $<\sigma[j], \sigma[k]> \notin E'$ then
10:                $E' \leftarrow E' \cup \{<\sigma[j], \sigma[k]>\}$
11:            if $\sigma[j] \notin N'$ then
12:                $N' \leftarrow N' \cup \{\sigma[j]\}$
13:                $traversalQueue.enqueue(\sigma[j])$
14: return $PIDG(N', E')$
```

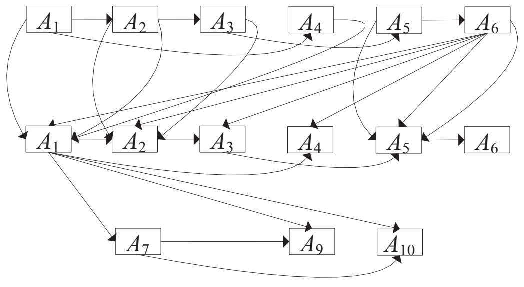


Fig. 4. PIDG of the IDG in Fig. 3.

Example 4 (Continuation of Example 3). *According to Algorithm 2, we obtain the trace slices for the variables in $ReachingDefs(P_1, \sigma) \uparrow D_2 = \{tourRequest_{A_1}, tourResponse_{A_2}, tourAcknow_{A_5}, passportInfo_{A_7}, flightInfo_{A_9}, hotelInfo_{A_{10}}\}$. Since activity A_8 is not involved in these obtained trace slices, A_8 and its edges are not contained in the final PIDG depicted in Fig. 4.*

4.3.3 Checking Migration Validity

Instead of trying to replay the original trace σ in the new process version P_2, our goal is to replay activities in the PIDG of σ. To guarantee the consistent state, during replaying, the replaying order of the two activities in the PIDG can be arbitrary if there is no direct or indirect dependences between them. Otherwise, their replaying order should be consistent with the dependence between them. This observation inspires us to define a more relaxed sufficient condition for migration validity checking.

Theorem 3. *Given two process versions $P_1 = (N_1, F_1, D_1, I_1, O_1)$, $P_2 = (N_2, F_2, D_2, I_2, O_2)$, and an instance I of P_1, whose current state and completed trace are s and σ respectively, if there exists a topological ordering ρ of the activities in the PIDG of σ such that ρ can be replayed in P_2, then the migration of I from P_1 to P_2 is valid.*

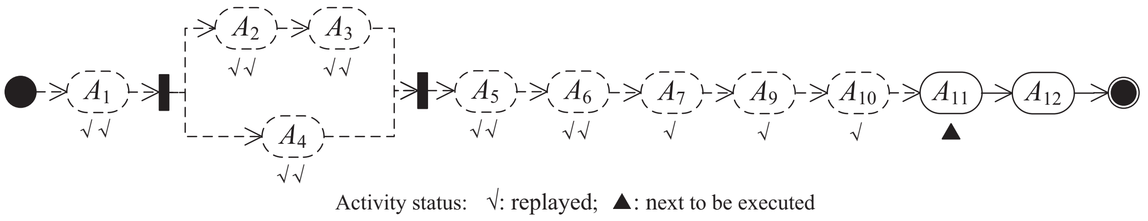


Fig. 5. Target control-flow state of the migration of I from P_1 to P_2 in Fig. 1.

Proof. IDG construction shows that the IDG (also the PIDG) is a DAG. Assume that there is a topological ordering ρ of the activities in the PIDG such that activities in ρ can be successively completed in P_2, and s' is the state of P_2 after ρ is replayed. $ReachingDefs(P_2, \rho)$ and $D_2 \setminus ReachingDefs(P_2, \rho)$ denote the variables in V_2 that have been assigned values and have not been assigned values in state s', respectively. Since ρ is a topological ordering of the activities in the PIDG of σ, it follows that $ReachingDefs(P_2, \rho) = ReachingDefs(P_1, \sigma) \uparrow D_2$. According to compiler theory for parallel execution of program statements [47], we conclude that for any variable $v \in ReachingDefs(P_2, \rho)$, $s(v) = s'(v)$. Therefore, (I) for each variable $v \in ReachingDefs(P_2, \rho)$, we have $(S(s))(v) = s(v) = s'(v)$; (II) for each variable $u \in (D_1 \cap D_2) \setminus ReachingDefs(P_2, \rho)$, $s(u)$ and $s'(u)$ are both undefined, thus $(S(s))(u)$ as well; (III) for each variable $w \in D_2 \setminus D_1$, $s'(w)$ is undefined since no activity of P_2 in σ' can assign value to w. (IV) Let $S(PC,\ M_1) = (PC,\ M_2)$, where M_1 and M_2 are control-flow states obtained after σ and ρ are replayed in P_1 and P_2, respectively. Altogether, $S(s) = s'$. According to Definition 6, the migration of I is valid and s' is the target state in P_2 for the migration. □

According to Theorem 3, the migration validity of an instance is checked as follows. First, only activities in the PIDG with no incoming edges can be selected to determine whether they can be replayed in the current state of P_2. After one such activity A_i is replayed, the current state of P_2 is updated; A_i and its edges are deleted from the PIDG. The above step is repeated until no activity satisfies this condition. When the procedure terminates, if the PIDG becomes empty, the instance's migration is valid. Otherwise, the procedure is terminated in advance, which indicates that the migration of the instance is not allowed by our approach.

Algorithm 3 is presented to check migration validity of an instance I (with trace σ) from the old process version P_1 to a new version P_2. The input of Algorithm 3 involves P_2 and the PIDG of the trace σ. Its output includes the migration validity result and the corresponding target state. Algorithm 3 works as follows. First, Lines 4-6 compute the indegree of each node (activity) and Lines 7-8 insert the nodes whose indegrees are zero into a set $zeroInNodeSet$. Line 10 checks whether there is an activity in $zeroInNodeSet$ that can be executed in the current state (P_2, M_c) of P_2. The notation (P_2, M_c) [A_i>(P_2, S_c′) which is inspired by Petri nets [52] denotes that A_i can execute in the state (P_2, M_c) and its execution results in a new state (P_2, M_c′). If there is no such activity, migration validity is not satisfied and the algorithm terminates (cf. Line 18). Otherwise, Line 11 removes n_i from $zeroInNodeSet$; Line 12 updates the current state of P_2; Lines 13-14 decrease the indegrees of the nodes adjacent to n_i. A node is added to $zeroInNodeSet$ once its indegree falls to zero (cf. Lines 15-16). The above procedure (i.e., Lines 9-18) iterates until $zeroInNodeSet$ becomes empty. If there is a topological ordering of the nodes (activities) in the PIDG that can be replayed in P_2, migration validity is satisfied and the target (control-flow) state for the migration is also obtained (cf. Line 19).

Algorithm 3 Check migration validity

```
Input: the new process version $P_2$ whose initial control-flow state is $M_0$; the pruned instance dependence graph $PIDG(N', E')$ of the input trace $\sigma$
Output: the migration validity result $validity$; the target state $targetState$
1: $validity \leftarrow$ "false", $targetState \leftarrow \emptyset$, $zeroInNodeSet \leftarrow \emptyset$
2: $(P_2, M_c) \leftarrow (P_2, M_0)$
3: for each $A_j \in N'$ do
4:     $indegree[A_j] \leftarrow 0$
5:     for each $<A_i, A_j> \in E'$ do
6:         $indegree[A_j] \leftarrow indegree[A_j] + 1$
7:     if $indegree[A_j] \neq 0$ then
8:         $zeroInNodeSet \leftarrow zeroInNodeSet \cup \{A_j\}$
9: while $|zeroInNodeSet| = 0$ do
10:    if $\exists A_i \in zeroInNodeSet$ with $(P_2, M_c)[A_i\!> (P_2, M_c')$ then
11:        $zeroInNodeSet \leftarrow zeroInNodeSet \setminus \{A_i\}$
12:        $(P_2, M_c) \leftarrow (P_2, M_c')$
13:        for each $A_j \in N'$, with $<A_i, A_j> \in E'$ do
14:            $indegree[A_j] \leftarrow indegree[A_j] - 1$
15:            if $indegree[A_j] = 0$ then
16:                $zeroInNodeSet \leftarrow zeroInNodeSet \cup \{A_j\}$
17:    else
18:        return ($validity$, $targetState$)
19: $validity \leftarrow$ "true", $targetState \leftarrow (P_2, M_c)$
20: return ($validity$, $targetState$)
```

Example 5 (Continuation of Example 4)**.** *From the PIDG in Fig. 4, it follows that the indegree of the first occurrence of A_1 is zero. According to Algorithm 3, the first occurrence of A_1 is selected to be replayed in the new process version P_2 which then goes from the initial state to a new state. At the same time, the first occurrence of A_1 and its outgoing edges are removed from the PIDG. Then, since only the indegree of the first occurrence of A_2 becomes zero, the first occurrence of A_2 is selected to be replayed in P_2. The above steps iterated until the PIDG becomes empty, i.e., all activities in the PIDG have been replayed in P_2 (A_1-A_6 are replayed twice because two occurrences of them are in the PIDG). The emptiness of the PIDG indicates that the migration of I from P_1 to P_2 is valid. The current control-flow state (A_{11} is ready to execute) of P_2 is also obtained for state mapping (cf. Fig. 5).*

4.4 Complexity Analysis

Finally, we analyze the time complexity of the algorithms introduced in Section 4.3.

Algorithm 1 is proposed to construct the IDG of σ, and to obtain the reaching definitions at the end of σ. The time cost of building the IDG is O($|N|$+$|E|$), where $|N|$ and $|E|$ represent the number of activities and activity dependences in σ, respectively. During each step of the IDG construction, the dynamic reaching definitions in the set $Defs$ needs updating and each updating has to traverse the set $Defs$. Assume k is the maximum number of output variables for all activities in σ. It can be shown that the time cost of obtaining $ReachingDefs(P_1, \sigma)$ is O($k^2 \times |N|^2$). Altogether, the time complexity of Algorithm 1 is O($K^2 \times |N|^2$+$|N|$+$|E|$).

Algorithm 2 is used to derive the PIDG from the IDG. Assume that the maximum number of output variables for all activities in σ is k, and thus the number of variables in $ReachingDefs(P_1, \sigma)$ is at most $k \times |N|$, where N is the node set of the input IDG. If the number of variables in P_2 is $|D_2|$ = m, the time cost of Line 2 in Algorithm 2 is O($m \times k \times |N|$). Since Lines 3-13 are responsible for constructing the PIDG, the running time cost is O($|N'|$+$|E'|$) but in the worst case it is O($|N|$+$|E|$). Thus, the time complexity of Algorithm 2 is O($m \times k \times |N|$+$|E|$).

The time complexity of Algorithm 3 is analyzed as follows. If the migration validity is satisfied, Algorithm 3 determines a topological ordering of activities in $PIDG(N', E')$ such that it can be replayed in the new process version P_2. In this case, the running time cost is O($|N'|$+$|E'|$). Otherwise, the replaying procedure terminates in advance, so the time cost is less than O($|N'|$+$|E'|$). To summarize, the time complexity of Algorithm 3 is O($|N'|$+$|E'|$).

5 Implementation

To validate our approach separately, we implemented it in Java as a proof-of-concept standalone prototype called Dilepis.[1] The functionality realized in Dilepis serves to determine the migration validity of process instances subject to dynamic evolution. Dilepis works with three input files: an original process version P_1, a new process version P_2, and a collection of traces of the running instances of P_1. Without loss of generality, the first two input files in our implementation are formatted in WS-BPEL [33], which is the de facto standard for data-aware business processes. The third input is imported as an XES file [34], which summarizes a set of traces of running instances. XES is the standard for business process event logs in the domain of process mining [34]. The output of Dilepis is the migration validity results of all traces (instances) in the input XES file.

Fig. 6 illustrates the architecture of Dilepis that consists of three layers: data layer, analysis layer, and presentation layer. The analysis layer contains three principal levels of components. The components at the bottom level comprise parsers of data-aware (WS-BPEL) processes and traces. `Process Parser` transforms WS-BPEL processes into our data-aware process models (cf. Definition 1). `Trace Parser` extracts traces (event sequences) from XES files.

1. The name Dilepis is the Spanish word for Chameleon; it is inspired from the animal's ability to support seamless change (of color).

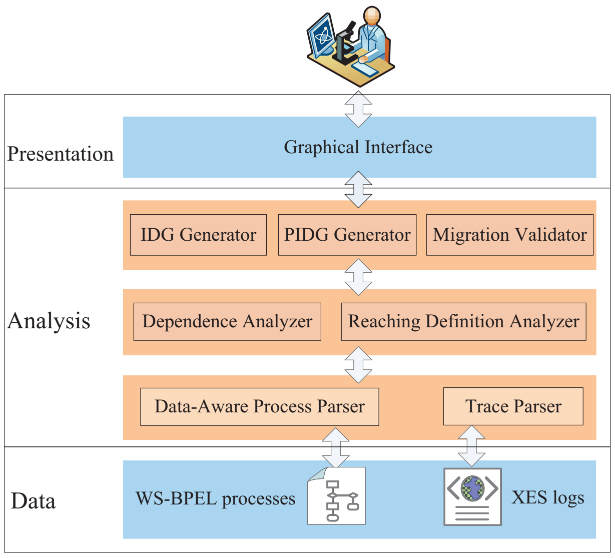


Fig. 6. Architecture of Dilepis.

In the extracted event sequence σ, each event e_i = (A_i, in, out) $\in \sigma$ corresponds to an activity, where A_i is the activity name and in/out refers to activities' input/output variables. At the second level, `Dependence Analyzer` obtains the control dependences in the process and analyzes data dependences in the traces parsed from the XES file. `Reaching Definition Analyzer` obtains the reaching definitions at the end of each trace according to the data flow analysis shown in Algorithm 1. The top level includes three components: `IDG Generator`, `PIDG Generator`, and `Migration Validator`. These three components implement the three steps (i.e., Algorithms 1, 2, 3) of our approach, respectively.

We also use Dilepis to perform the experiment in Section 6. Dilepis and the data sets employed in the experiment are all publicly available at http://bit.ly/myDilepis.

Finally, we discuss how our approach Dilepis can be used by process engines. Our approach needs to be realized as a module of the process engine. The module is used by the engine to determine, when the process evolves from P_1 to P_2, whether a running instance I of P_1 in its current state can be migrated to P_2 to continue execution. If so, the process engine needs to copy the state s of I from P_1 to P_2, according to the state mapping S provided by our approach. Then, the process engine orchestrates I to continue execution from the state $S(s)$ in P_2. Otherwise, the process engine resumes execution of I according to P_1.

It is worth mentioning that although the execution of some activities in the process is not instantaneous, these activities are atomic operations. That is, the effect (output) of an activity can only be stored in the instance state after the activity completes the execution [37], [32], [18], and thus there is no middle state during its execution. Since process engines manage the state of the instance, as well as the lifecycle of each activity, migration checking can be conducted when all active activities of the process instance complete.

TABLE 2
Migration Criteria (Approaches) Compared in the Experiment

Ref.	Migration criteria (approaches)
WIDE	The approach proposed in [14]
ADEPT	The approach proposed in [32]
Dilepis	Our IDG-based approach

6 Evaluation

In this section, we conduct an extensive experiment followed by an intensive case study to evaluate our approach, and compare it with state-of-the-art approaches that are based on trace replaying (cf. Table 2). Note that our evaluation only focuses on the migration criteria and the corresponding checking methods instead of comparing whether the approaches can allow the instances that do not satisfy migration validity to be migrated with the help of extra measures. Although the ADEPT framework provides more advanced strategies to improve the number of instances that can be migrated [55], to allow for a well-scoped and fair comparison, these strategies are not considered in our evaluation because they are orthogonal to migration validity checking.

6.1 Experiment

Initially, we present our experimental evaluation by comparing our approach with approaches in Table 2. The experiment is performed on a PC with 2.4GHz Intel i5-4210U processor and 4GB memory running Windows 8 and Java SE 6.0. Through the experiment, we study the following two research questions:

1) **RQ1**: Effectiveness - Empirically, does our approach allow more instances to migrate than existing approaches do?
2) **RQ2**: Efficiency - Does our approach scale?

6.1.1 Experimental Setup

Data set and experimental procedure. Ideally, we need a set of data-aware processes before and after evolution as well as a set of to-be-migrated instances to conduct the experiment. Unfortunately, there is no widely-acknowledged data set suitable for our experiment. To fully explore the performance of different approaches, we employ a total of 41 real-world WS-BPEL processes to generate the required data set. These WS-BPEL processes were downloaded from the Reo project website[2], divided into several categories including "`FromBPELSpec`", "`FromIBM`", "`FromOracle`", and "`FromQUT`".

For each WS-BPEL process, we first generate a collection of its traces (not complete). Then, we randomly modify a certain proportion of the overall traces to derive trace variants. We note that each variant is obtained by one modification only, that is, deleting one activity, adding one activity, and swapping the order of two activities. Other change scenarios can be transformed into the above three cases. The manner of introducing variants is inspired by fault seeding practiced in software testing [56], [57], [58], [59], which is discriminative to study the performance of different approaches in different process evolution scenarios. Our experiment is performed on four data sets. The first one contains trace variants that are obtained by deleting one activity from the corresponding compliant traces. The second one involves trace variants which are obtained by adding one activity to the corresponding compliant traces. The third one includes trace variants that are acquired by swapping the order of two activities in the corresponding compliant traces. The last one involves trace variants of the above three different kinds. Each of these four data sets consists of nine subsets. Each of the subsets contains 30 traces with a proportion (from 10 percent to 100 percent) of trace variants. As a consequence, 41 WS-BPEL processes and 41×4×10×30 = 49,200 traces in total are employed in our experiment. Suppose that the variants are traces of the instances of the old process version P_1 (that do not really exist) and the corresponding WS-BPEL process is the new process version P_2 after evolution. Under this assumption, we check whether the migrations of those instances to P_2 are valid according to different migration criteria (i.e., approaches). After this, different approaches are compared based on the evaluation criteria introduced later. Notably, the reason why we modify traces to obtain trace variants instead of modifying processes to obtain process variants is that process changes occurring to the "future" of instances do not prevent instance from being migrated.

Evaluation criteria. Since the problem of instance migration validity checking is undecidable, the oracle (ground true) of whether a process instance satisfies migration validity is unavailable in our experiment. Consequently, we cannot compute the false positives and false negatives as usual. As Dilepis and the improved WIDE (when variable state is considered) correspond to two sufficient conditions of the problem, we employ the following two criteria (that is, *migration rate*, *migration factor* [32]) to evaluate and compare the effectiveness of the three different approaches. We denote a collection of instances (traces) of a process P as $InstanceSet_P$, and the set of instances that can be migrated to the new process version based on the migration criterion (approach) $MC \in \{$WIDE, ADEPT, Dilepis$\}$ as $InstanceSet_{(MC)}$. The migration rate $MR_{(MC)}$ is used to measure the proportion of migratable instances by using different approaches, and the migration factor $MF_{(MC_1 \to MC_2)}$ is utilized to measure the increase of the migration rate when going from the migration criterion MC_1 to the migration criterion MC_2:

$$MR_{(MC)} = \frac{|InstanceSet_{(MC)}|}{|InstanceSet_P|} \tag{1}$$

$$MF_{(MC_1 \to MC_2)} = \frac{|InstanceSet_{(MC_2)}| - |InstanceSet_{(MC_1)}|}{|InstanceSet_P|} \tag{2}$$

Furthermore, since each of the three approaches compared in the evaluation also returns a "target state" in the new process P_2 if an instance is allowed to migrate, we can manually validate whether this "target state" s' is consistent with the instance state s before the migration. If they are not consistent (can be checked by comparing variable state),

2. http://reo.project.cwi.nl/reo/

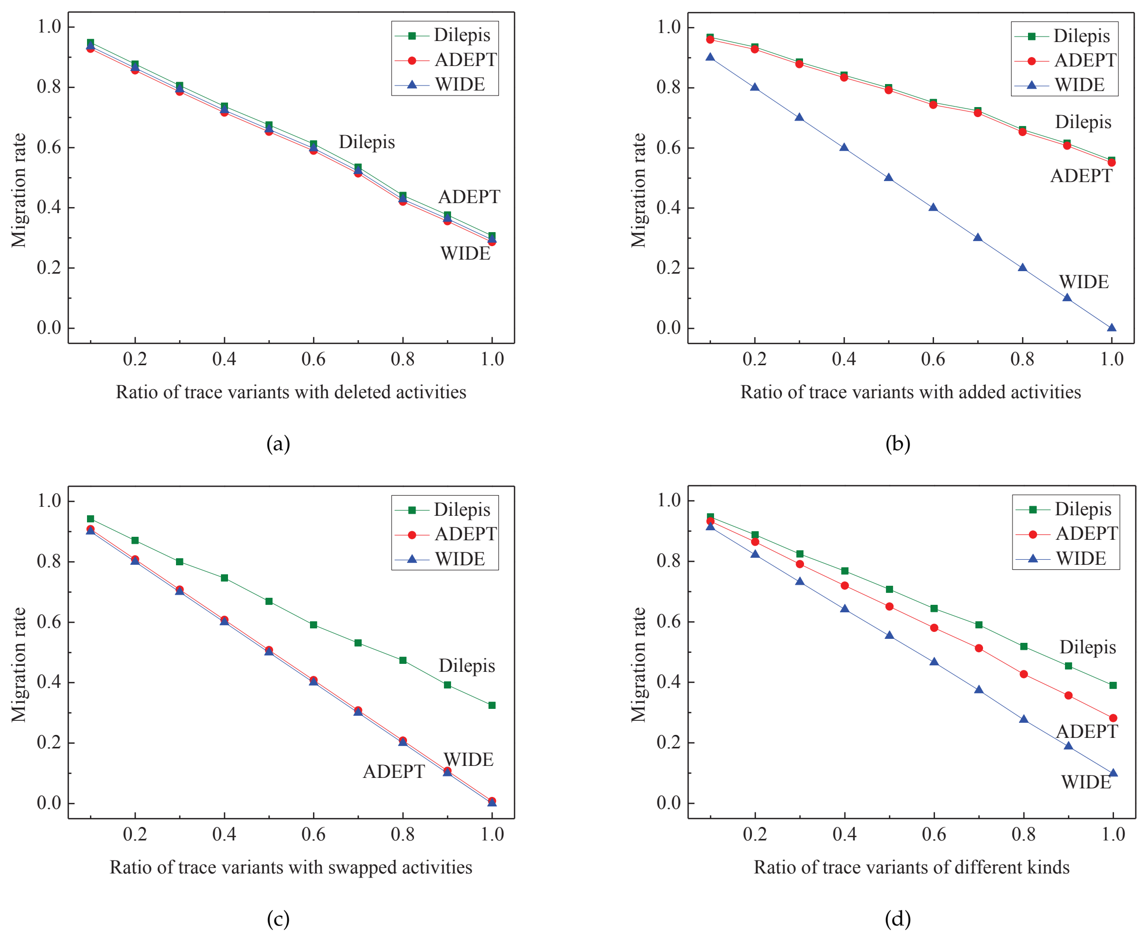


Fig. 7. Experimental results of migration rates on four data sets.

a false positive is generated. Through this manual check, we confirm our theoretical results that both WIDE (when variable state is considered) and our approach Dilepis do not produce false positives. However, the ADEPT approach may produce false positives, because when taking the variable state into account, certain "target states" returned by ADEPT are not consistent with the instance states in P_1, i.e., the values of some variables are different.

Also, the efficiency of an approach to migration validity checking is an important consideration. An inefficient approach could impact the quality of service properties of a process or even result in the failure of some real-time safety-critical systems. Hence, in the experiment, we also investigate the efficiency (i.e., runtime overheads) of different approaches to migration validity checking.

6.1.2 RQ1: Effectiveness

Experimental results of migration rates. Fig. 7 illustrates the average migration rates generated by the three approaches summarized in Table 2 on the four data sets.

From Fig. 7a, it follows that the migration rates of all three approaches decrease with the increasing ratio of trace variants in the first data set. We also find that, when the ratio of trace variants is fixed, the migration rate remains stable regardless of the migration criteria (approaches) used. In other words, the performance of the three approaches on the first data set is similar. By manually checking the consistency between the "target states" returned by different approaches and the instance state before migration, we find that neither approach creates false positives in this case. Therefore, compared with the WIDE approach, both approaches of ADEPT and Dilepis fail to increase the number of migratable instances, when process evolution only adds new activities to the instance's "history" (i.e., the completed process fragment) in the new process version. In fact, adding activities to the "history" is the major reason leading to migration failure, because it is hard to find in the new version a reachable state that is consistent with the current state of the running instance in the old version. So far, to the best of our knowledge, there is no better migration criterion that could raise the migration rate in this type of process evolution.

From Fig. 7b, it can be seen that the migration rates of all three approaches decrease with the growing ratio of trace variants in the second data set. Nevertheless, both the ADEPT approach and our approach (Dilepis) perform better than the WIDE approach (i.e., the traditional trace replaying). Specifically, the first two approaches allow more instances to be migrated than the WIDE approach does. This indicates that process evolution that deletes activities from the instance's "history" in the new process version can greatly affect the migration rate of WIDE. Fortunately,

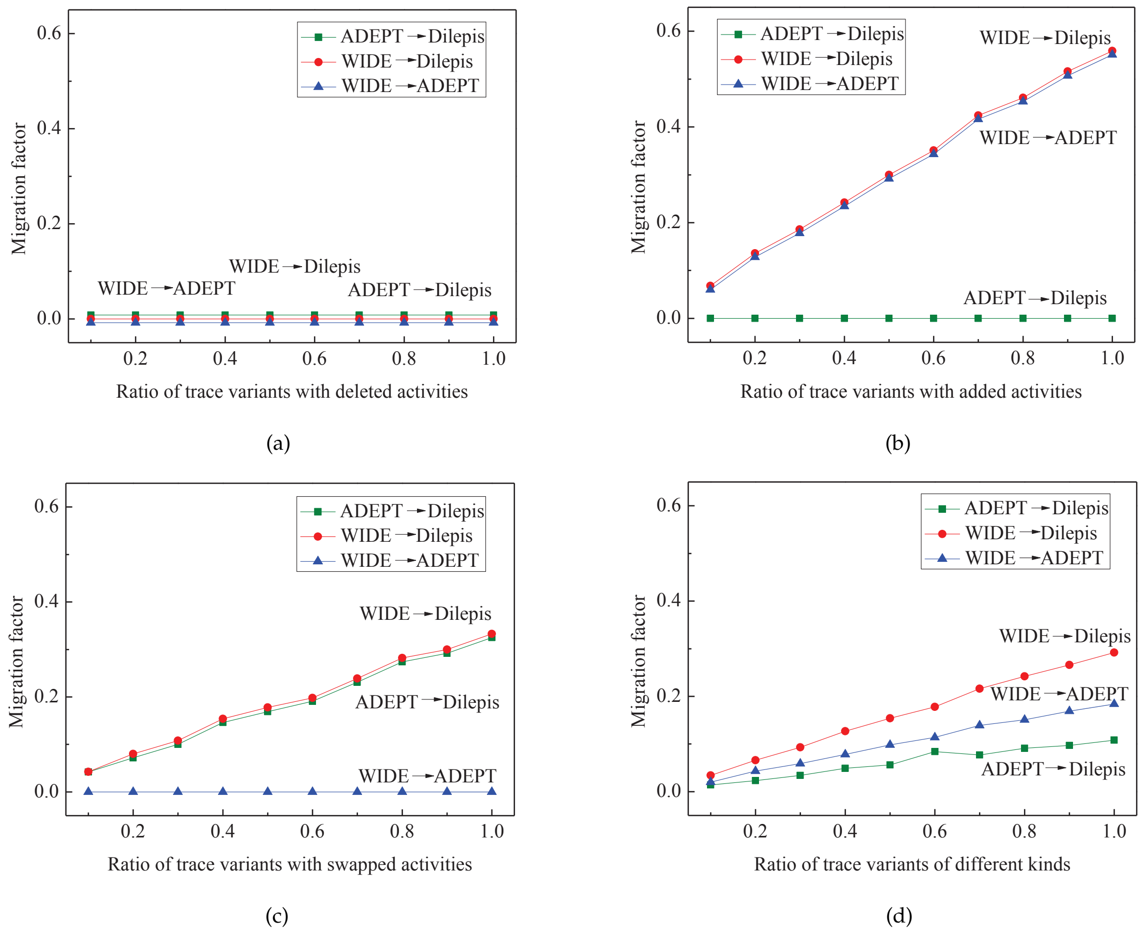


Fig. 8. Experimental results of migration factors on four data sets.

the influence on the other two approaches is not significant, because some deleted activities do not affect the state mapping. In this type of process evolution, ADEPT and Dilepis are more relaxed than WIDE. However, ADEPT is not sound when variable state is taken into consideration, and thus it may produce false positives. By manually checking the "target states" returned by different approaches, we find that the proportion of false positives generated by ADEPT is 23.4 percent, whereas WIDE and Dilepis do not produce false positives. In the experiment, we discarded the false positives generated by ADEPT, and therefore the performance of ADEPT and Dilepis is comparable.

Fig. 7c reveals that the migration rate of our approach (Dilepis) is higher than that of the other two approaches. That is, Dilepis allows more instances to be migrated than the other two approaches do. By manually checking the "target states" returned, we find that neither approach generates false positives in this case. This result demonstrates that process evolution that swaps activities in the instance's "history" can greatly affect the migration rate of both WIDE and ADEPT. On the other hand, the impact on Dilepis is not significant, because swapping activities without dependences does not affect the state mapping in our approach. Thereby, our approach is more relaxed than the other two approaches for this type of process evolution.

Fig. 7d illustrates that our approach (Dilepis) allows more instances to be migrated than the other two approaches (i.e., WIDE, ADEPT) do. This result demonstrates that, overall, our approach is more relaxed than the other two approaches. In summary, ADEPT may produce false positives for instance migration validity checking, when certain activities are deleted during process evolution. In contrast, WIDE and Dilepis do not create false positives in any case, which confirms Theorems 2 and 3.

Experimental results of migration factors. Figs. 8a-8d reveal the average migration factors on the four data sets, respectively. These figures reflect a similar rule as Figs. 7a-7d do.

As Fig. 8a shows, with the increasing ratio of trace variants in the first data set (the process evolution scenario is inserting activities into the instance's "history"), there is few increase in migratable instances when going from the migration criterion WIDE to the migration criterion ADEPT and Dilepis. From Fig. 8b, it follows that with the growing ratio of trace variants in the second data set (the process evolution scenario is deleting activities from the instance's "history"), there is an increase in the proportion (from 6 percent to 55.1 percent) of migratable instances when going from the migration criterion WIDE to the migration criteria ADEPT and Dilepis. Fig. 8c demonstrates that with the rising ratio of trace variants in the third data set (the process evolution scenario is swapping activities in the instance's "history"), there is a significant increase in the proportion

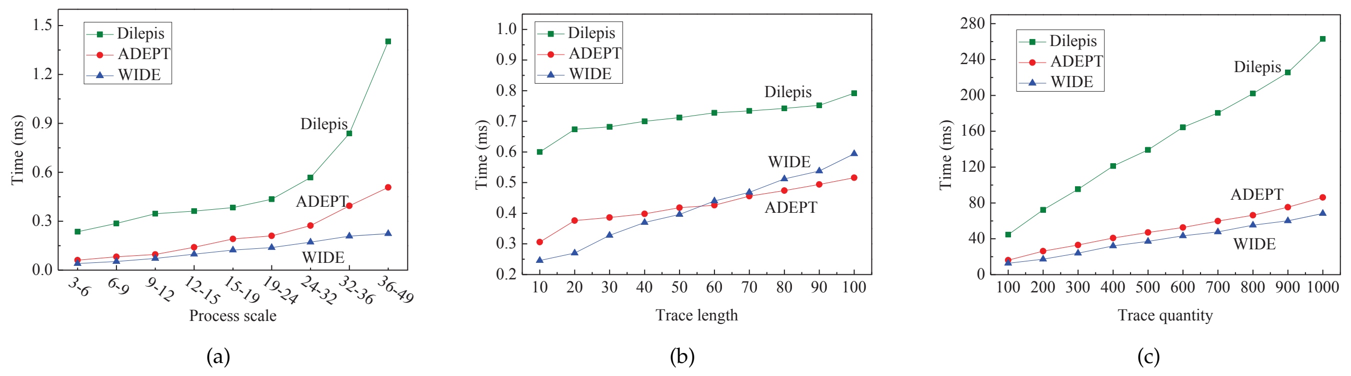


Fig. 9. Experimental results on efficiency: (a) Runtime costs with respect to process scale, (b) Runtime costs with respect to trace length, (c) Runtime costs with respect to trace quantity.

(from 4.2 percent to 32.5 percent) of migratable instances when going from the migration criteria WIDE and ADEPT to the migration criterion Dilepis. Fig. 8d illustrates that with the increasing ratio of trace variants in the fourth data set (with different evolution scenarios), there is an increasing proportion (from 3.4 percent to 29.2 percent) of migratable instances when going from the migration criterion WIDE to the migration criterion Dilepis, and also there is an increasing proportion (from 1.4 percent to 10.8 percent) of migratable instances when going from the migration criterion ADEPT to the migration criterion Dilepis.

6.1.3 *RQ2: Efficiency*

To evaluate the efficiency of our approach, we record runtime overheads of different approaches in our experiment.

Figs. 9a, 9b, and 9c illustrate the average runtime costs of different approaches with the increase in process scale (i.e., the number of activities in a process), trace length (i.e., the number of activities in a trace), and trace quantity (i.e., the number of to-be-migrated instances), respectively. From Fig. 9, it can be seen that:

Overall, WIDE is the most efficient approach. However, when the process involves loops and the trace contains many iterations of activities in loops (this is the reason why the trace length shown in Fig. 9b can be greater than 50), ADEPT is the most efficient approach. This is because activity iterations except the last one are deleted from the trace by ADEPT before the trace is replayed. Compared with the other two approaches, our approach (Dilepis) is the most inefficient. This is unsurprising, because our approach needs more time to obtain the IDG (also PIDG) and the reaching definitions at the end of the trace. However, it is worth the effort, as our approach gives rise to more migratable instances than the other two approaches do.

Our approach and the other two approaches scale well with the increase of process scale, trace length, and trace quantity, respectively. The runtime overhead of our approach can be neglected for long-running, real-world business processes. Even for some real-time, safety-critical business processes, the overhead (less than 1-2 milliseconds in our experiment) of our approach would be acceptable.

6.2 Case Study

Here, we present a case study to demonstrate the effectiveness and advantages of our approach. The case study stems from two real-world WS-BPEL applications: `Auction` and `MarketPlace`[3]. Although these processes are named differently, they share similar functionalities; that is, they both act as intermediaries between sellers and buyers. Based on these applications and their variants, four versions of the marketplace service (process) are constructed. Note, similar services and applications are frequently used in the literature on service-based software engineering, e.g., [48], [57], [17], [21], [60], [39], [61], [58], [59], [46].

Fig. 10a shows the UML activity diagram to present the first version V_1 of the marketplace process. It initially receives the requests from the seller and the buyer in parallel. If the price ($buyerInfo.offer$) offered by the buyer is not lower than the expected price ($sellerInfo.askingPrice$) of the seller, the trade is successful, and, according to the marketplace operation policies, the marketplace process invokes the trade registration service to register the transaction; otherwise, the trade fails. In the end, the trade outcome, regardless of success or failure, is conveyed to seller and buyer. Operational analysis conducted at the marketplace reveals, that a buyer often waits for a long time for a seller due to the imbalance between supply and demand. In order to reduce the waiting time of the buyer, the marketplace owner modifies the process to first receive seller requests and then buyer request. In addition, the process is further improved by notifying seller and buyer of the trade outcome in parallel. These two changes result in a new process version V_2 (cf. Fig. 10b). Also, the marketplace process may be affected by changes in the environment. For example, the trade registration service updates its interface, which calls for a request-response <invoke> activity to interact with it. To adapt to this change, the two activities A_5 and A_6 are replaced by a new activity A_{10} in the third process version V_3 shown in Fig. 10c. Finally, the marketplace process evolves to the process version V_4 shown in Fig. 10d, when the operational policy to register trades is cancelled.

Table 3 lists a set of running process instances of V_1, where the trace of each process instance and the reaching

3. https://neptuno.uca.es/svn/wsbpel-comp-repo/

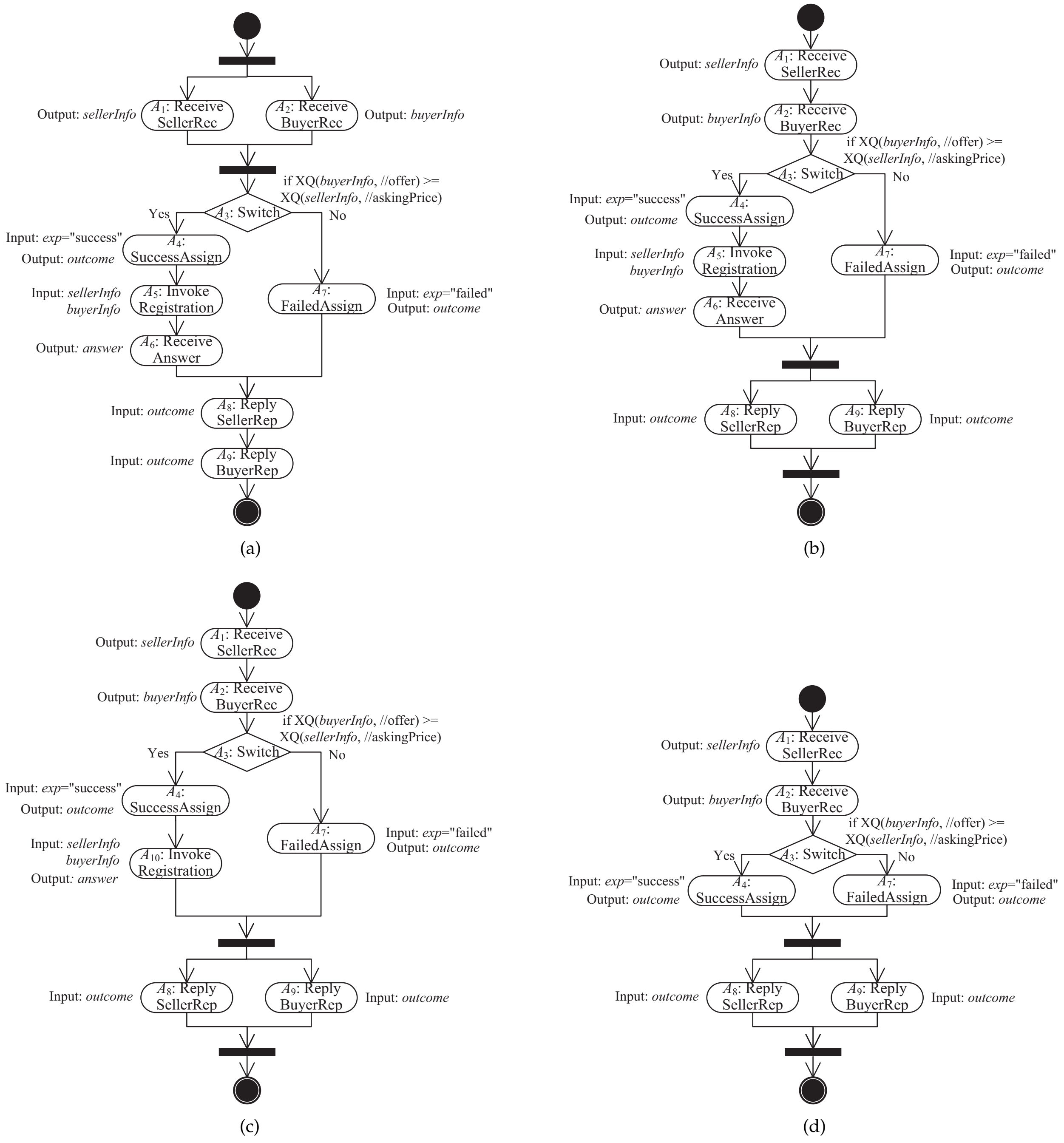
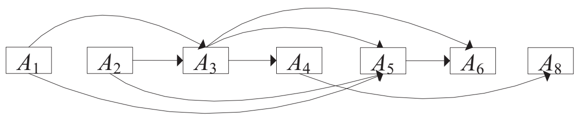


Fig. 10. Four versions of a marketplace process.

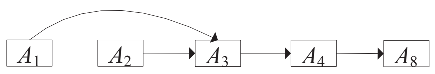
definitions at the end of the trace are given. In the following, we investigate whether these process instances can be migrated to V_2, V_3, and V_4 according to the different approaches. Other scenarios, such as instance migrations from V_2 to V_3 and V_4, are also possible. Let us first analyze I_1. Since its trace σ_1 can be replayed in V_2 rather than V_3 and V_4, WIDE only allows I_1 to migrate to V_2. Similarly, ADEPT allows I_1 to migrate to V_2. Note, although activity A_{10} and A_5 share the same name, their signatures (input and output) are different, thus, they constitute different activities. In order to investigate whether I_1 can migrate to V_3 according to ADEPT, we first need to obtain its reduced trace $\sigma'_1 = A_1A_2A_3A_4A_8$ with respect to V_3. Since σ'_1 cannot be replayed in V_3, ADEPT does not allow I_1 to migrate to V_3. Since the reduced trace $\sigma''_1 = A_1A_2A_3A_4A_8$ with respect to V_4 can be replayed in V_4, ADEPT allows I_1 to migrate to V_4. When Dilepis is used, we first obtain the IDG (instance dependence graph) of I_1. Then, we derive the PIDG (pruned instance dependence graph) with respect to the new version V_2 (V_3, V_4). Fig. 11a presents the IDG of I_1, which is also the PIDG of I_1 with respect to V_2 (V_3). Since $answer \in \mathit{ReachingDefs} \cap V(P_3)$, activities A_5 and A_6 are retained in the PIDG. Fig. 11b presents the PIDG of I_1 with respect to V_4. Finally, since there is a topological sort of the nodes in Fig. 11a (Fig. 11b), i.e., $\rho_1 = A_1A_2A_3A_4A_5A_6A_8$ ($\rho'_1 = A_1A_2A_3A_4A_8$), which can be replayed in V_2 (V_4), Dilepis

TABLE 3
A Set of Process Instances of the Marketplace Process V_1

Instance	Trace	Reaching definitions
I_1	$\sigma_1 = A_1A_2A_3A_4A_5A_6A_8$	$sellerInfo_{A_1}, buyerInfo_{A_2}, outcome_{A_4}, answer_{A_6}$
I_2	$\sigma_2 = A_2A_1A_3A_4A_5A_6A_8$	$buyerInfo_{A_2}, sellerInfo_{A_1}, outcome_{A_4}, answer_{A_6}$
I_3	$\sigma_3 = A_1A_2A_3A_4A_5A_6$	$sellerInfo_{A_1}, buyerInfo_{A_2}, outcome_{A_4}, answer_{A_6}$
I_4	$\sigma_4 = A_2A_1A_3A_4A_5A_6$	$buyerInfo_{A_2}, sellerInfo_{A_1}, outcome_{A_4}, answer_{A_6}$
I_5	$\sigma_5 = A_2A_1A_3A_7A_8$	$buyerInfo_{A_2}, sellerInfo_{A_1}, outcome_{A_7}$
I_6	$\sigma_6 = A_1A_2A_3A_7A_8$	$sellerInfo_{A_1}, buyerInfo_{A_2}, outcome_{A_7}$
I_7	$\sigma_7 = A_2A_1A_3A_4A_5$	$buyerInfo_{A_2}, sellerInfo_{A_1}, outcome_{A_4}$
I_8	$\sigma_8 = A_1A_2A_3A_4A_5$	$sellerInfo_{A_1}, buyerInfo_{A_2}, outcome_{A_4}$
I_9	$\sigma_9 = A_1A_2A_3A_7$	$sellerInfo_{A_1}, buyerInfo_{A_2}, outcome_{A_7}$
I_{10}	$\sigma_{10} = A_2A_1A_3A_7$	$buyerInfo_{A_2}, sellerInfo_{A_1}, outcome_{A_7}$
I_{11}	$\sigma_{11} = A_1A_2A_3A_4$	$sellerInfo_{A_1}, buyerInfo_{A_2}, outcome_{A_4}$
I_{12}	$\sigma_{12} = A_2A_1A_3A_4$	$buyerInfo_{A_2}, sellerInfo_{A_1}, outcome_{A_4}$
I_{13}	$\sigma_{13} = A_1A_2A_3$	$sellerInfo_{A_1}, buyerInfo_{A_2}$
I_{14}	$\sigma_{14} = A_2A_1A_3$	$buyerInfo_{A_2}, sellerInfo_{A_1}$
I_{15}	$\sigma_{15} = A_1A_2$	$sellerInfo_{A_1}, buyerInfo_{A_2}$
I_{16}	$\sigma_{16} = A_2A_1$	$buyerInfo_{A_2}, sellerInfo_{A_1}$
I_{17}	$\sigma_{17} = A_1$	$sellerInfo_{A_1}$
I_{18}	$\sigma_{18} = A_2$	$buyerInfo_{A_2}$



(a)



(b)

Fig. 11. IDG and PIDG of I_1 of process version V_1: (a) IDG of I_1 and PIDG of I_1 with respect to process versions V_2 and V_3, (b) PIDG of I_1 with respect to process version V_4.

allows I_1 to migrate to V_2 (V_4), but does not allow I_1 to migrate to V_3, either.

Since both σ_2 and its reduced trace with respect to V_3 and V_4 cannot be replayed in V_2-V_4, neither WIDE nor ADEPT allows I_2 to migrate to V_2-V_4. However, similar to I_1, I_2 is allowed to migrate to V_2 and V_4 according to Dilepis, because I_2 and I_1 share the same IDG and PIDG. Since the target state, including control-flow state $PC = M = \{A_9\}$ and variable state (in terms of symbolic reaching definitions, i.e., $buyerInfo_{A_2}$, $sellerInfo_{A_1}$, $outcome_{A_4}$, $answer_{A_6}$), of I_2 returned by Dilepis corresponds to a reachable state of V_2, it is not a false positive to migrate I_2 to V_2. Similarly, the migration result that I_2 can migrate to V_4 is also not a false positive. In contrast, WIDE and ADEPT generate false negatives on the migration of I_2 to V_2 and V_4.

Neither approach allows I_2 (I_1) to migrate to V_3. This is because, the main idea of these three approaches is to reuse the completed activities of the process instance in V_1, whereas the newly-added activity A_{10} is absent from σ_2 (σ_1). On the other hand, the effect of A_{10} is equivalent to that of A_5 and A_6, which is only known to the process maintainer or programmer. Therefore, the current state s of I_2 (I_1) is consistent (same) with a reachable state of V_3. Therefore, I_2 (I_1) can be migrated to V_3, which implies that all the three approaches produce false negatives in this case. This example also illustrates the limitation of our approach. In fact, it is difficult to avoid such false negatives without the help of process maintainers.

Next, we analyze the migration validity of I_3. Since the original trace $\sigma_3 = A_1A_2A_3A_4A_5A_6$ of I_3 can be replayed in V_2 and can neither be replayed in V_3 nor in V_4, WIDE only allows I_3 to migrate to V_2. When ADEPT is used, we first obtain the reduced trace $\sigma_3' = A_1A_2A_3A_4$ of I_3 with respect to V_3 (V_4). Since σ_3' can be replayed in V_3 (V_4), I_3 is allowed to migrate to V_2, V_3, and V_4 according to ADEPT. However, after I_3 is migrated to V_3, A_{10} is the first activity to execute, and therefore the trade between seller and buyer is registered twice. This is not allowed by the registration service according to the registration policy. The migration of I_2 to V_3 may even lead to an exception. In fact, although activities A_5 and A_6 are deleted, their effect, i.e., the value of the variable $answer_{A_6}$ is still in the state I_3. According to our definition of migration validity (cf. Definition 6), the target state of I_3 returned by ADEPT is not a reachable state of V_3. Altogether, allowing I_2 to migrate to V_3 is a false positive of ADEPT. Similar to the migration validity analysis of I_1 and I_2, Dilepis allows I_3 to migrate to V_2 and V_4 rather than V_3.

The migration results of all process instances of V_1 listed in Table 3 can be determined similarly, which are summarized in Table 4. Since the number of reachable states of V_2 (V_3, V_4) is enumerable, false positives and false negatives of different approaches can be determined on the basis of the manual checking procedure outlined above. ADEPT produces two false positives, whereas WIDE and Dilepis do not produce false positives (cf. Table 5), which confirms our theoretical results. The number of false negatives generated by WIDE, ADEPT, and Dilepis are 29, 24, 4, respectively. This indicates that our approach avoids many false negatives

TABLE 4
Migration Validity Results of Process Instances in Table 3 according to Different Approaches

Instance	Migratable to V_2?			Migratable to V_3?			Migratable to V_4?		
	WIDE	ADEPT	Dilepis	WIDE	ADEPT	Dilepis	WIDE	ADEPT	Dilepis
I_1	Yes	Yes	Yes	No	No	No	No	Yes	Yes
I_2	No	No	Yes	No	No	No	No	No	Yes
I_3	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
I_4	No	No	Yes	No	No	No	No	No	Yes
I_5	No	No	Yes	No	No	Yes	No	No	Yes
I_6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
I_7	No	No	Yes	No	No	No	No	No	Yes
I_8	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
I_9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
I_{10}	No	No	Yes	No	No	Yes	No	No	Yes
I_{11}	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
I_{12}	No	No	Yes	No	No	Yes	No	No	Yes
I_{13}	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
I_{14}	No	No	Yes	No	No	Yes	No	No	Yes
I_{15}	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
I_{16}	No	No	Yes	No	No	Yes	No	No	Yes
I_{17}	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
I_{18}	No	No	No	No	No	No	No	No	No

TABLE 5
The Number of False Positives and False Negatives of the Results in Table 4

	False positives			False negatives		
	WIDE	ADEPT	Dilepis	WIDE	ADEPT	Dilepis
$V_1 \to V_2$	0	0	**0**	8	8	**0**
$V_1 \to V_3$	0	2	**0**	10	8	**4**
$V_1 \to V_4$	0	0	**0**	11	8	**0**
Overall	0	2	**0**	29	24	**4**

TABLE 6
Overall Results on the Migration Rate and Migration Factor

	Migration rate			Migration factor		
	WIDE	ADEPT	Dilepis	WIDE $\to$ ADEPT	ADEPT $\to$ Dilepis	WIDE $\to$ Dilepis
$V_1 \to V_2$	50%	50%	**94.4%**	0	44.4%	44.4%
$V_1 \to V_3$	33.3%	33.3%	**61.1%**	0	27.8%	27.8%
$V_1 \to V_4$	33.3%	50%	**94.4%**	16.7%	44.4%	61.1%
Overall	38.9%	44.4%	**83.3%**	5.5%	38.9%	44.4%

produced by the other two approaches. Based on these results, the migration rate of each approach can be calculated (false positives are excluded), as well as the migration factor from one migration criterion (approach) to another (cf. Table 6). These results demonstrate that, compared with WIDE and ADEPT, Dilepis allows more process instances to migrate to the new process version, without giving rise to false positives. Thus, we conjecture that Dilepis is promising in practice.

6.3 Threats to Validity

We analyze both construct validity and external validity for our experiment and case study.

Construct validity. The process models defined by WIDE, ADEPT, and Dilepis are different. In the process model of WIDE, only activity conditions are defined, whereas input and output variables are not defined. In the process model of ADEPT, activities are linked to data (variables) with "read" and "write" edges. In our process model (cf. Definition 1), each activity is associated with input and output variables, which constitutes a simpler representation. Since neither WIDE nor ADEPT are publicly available, and both approaches do not take variable state into account, we implemented and improved them according to their description in the literature based on our own data-aware process model. The re-implementation may introduce a threat to construct validity in our experimental results; mainly affecting runtime performance metrics which heavily depend on the implementation, i.e., the data structures used.

External validity. There are two main threats to the external validity of our empirical results. For one thing, we employ totally 41 WS-BPEL processes and their adapted trace variants for the migration experiment. For each WS-BPEL process, the trace variants are obtained through manual modification of the original compliant traces, and like fault seeding in WS-BPEL process testing [57], [58], [59], each trace variant is planted with only one modification (deleting one activity, adding one activity, swapping the order between two activities), which may fail to represent real-world cases (In fact, the experimental result of our approach is even better when different kinds of modifications are involved in a trace.). Moreover, since the processes before evolution are not actually available but they only exist theoretically, our experimental setup is not the same as real scenarios. For another, WS-BPEL processes are only one kind of data-aware processes. It needs further investigation whether the empirical results of our experiment and case study can be generalized to other data-aware processes. To minimize these two threats, we will try to evaluate different approaches with more real-world evolution scenarios of data-aware processes.

7 Discussion

In this section, we first introduce how session management of process instances is handled in our approach. Then, we discuss the strengths and limitations of our approach, as well as complementary techniques to further improve instance migration possibility.

Since data-aware processes are stateful, "session" management ought to be considered in migration validity checking. Let us explain how session is handled in our approach. For business processes, e.g., WS-BPEL processes, a session of a process instance can be characterized by the sequence of messages sent to or received from its "environment" (external services) [58]. Assume that P_1 and P_2 are the processes before and after the evolution, and I is a process instance of P_1. The "effect" of the session (message sequence) of I is reflected by the values of corresponding variables in the process. In particular, a WS-BPEL process instance, say, I, uses a <receive> activity to receive a message from its environment, and the received information is delivered to the output of the <receive> activity; I uses a one-way <invoke> (or <reply>) activity to send a message, and the information sent to its environment is encapsulated as the input of the <invoke> (<reply>) activity. I may also use the request-response <invoke> activity, which encapsulates the message sent in its input, and extracts the replied message in its output. In addition, WS-BPEL provides correlation mechanism (<correlation>) to guarantee that messages are delivered to the right process instances [33], [58]. Altogether, we conclude that the session is covered in the instance state, and thus our approach can handle it. This implies that if the session changes in the new version P_2, our approach does not allow the process instance to migrate.

The major reason for the migration invalidity is that the process evolution $\triangle$ changes the instance's "history". When variable state is taken into account, WIDE is too rigorous while ADEPT may create false positives for migration validity checking. The merit of our approach lies in that it allows the migration of I, if $\triangle$ refers to reordering, sequentializing, and parallelizing activities without dependences, or to just removing some irrelevant activities. However, our approach is limited to instance migration validity at the syntactic level (i.e., control flow and data flow), while semantic constraints (e.g., domain knowledge) and temporal constraints in business processes are not considered [62]. Consequently, some instances that violate semantic and temporal constraints may be mistakenly allowed to be migrated by our approach. In addition, our approach does not consider other related issues and scenarios that are orthogonal to migration validity checking, e.g., the migration of deviating instances that result due to ad-hoc changes, how semantic rollback impacts migration validity, and how to apply instance-specific changes to further increase the number of migratable instances [55].

We learn from our study that "late changes" can raise the possibility of valid instance migration, that is, if the change (i.e., evolution) is applied near the end of the process, the number of migratable instances could raise. Thereby, if the effect of changing the front half of a process is the same as that of changing the second half part of a process, the latter is recommended. For example, assume that for an evolution scenario several related activities should be inserted into a process. If these activities do not control or data-dependent on the activities of the original process, we can add them at the end of the process, which definitely enhances the instance migration rate.

To improve the possibility of instance migration and to complement our approach, we employ two strategies: *delayed migration* and *rollback-based migration*. Although these strategies have been studied before, variable state is not explicitly considered in prior work. Also, the combination of our approach with these strategies can achieve better result. Chances are that the migration of an instance from its current state is invalid; however, when the instance continues execution, it may enter a state in which its migration is valid. In this case, the strategy of delayed migration becomes feasible. For example, in the case study presented in Section 6.2, I_{18} cannot be migrated to V_2 in its current state. Nonetheless, it can migrate in our approach, when it completes executing activity A_2. However, if the other two approaches, i.e., WIDE and ADEPT, are employed, I_{18} is not allowed to migrate. The reason for the migration invalidity lies in the fact that the instance has progressed too far, that is, the execution of the instance has already passed an evolution region of the process. With this in mind, the main idea of rollback-based migration is to erase the "effect" (variable value) of certain activities in the trace so that the instance is delivered to a state in which the migration is valid. Besides these two, more advanced migration strategies proposed in the ADEPT framework can also be used for reference [55].

8 Conclusions

This paper formulates the problem of instance migration and migration validity checking in the context of the dynamic evolution of data-aware processes. We first prove that the problem of migration validity checking is in general undecidable. Then, we analyze activity dependences in the trace of the to-be-migrated instance and capture them in an instance dependence graph (IDG). Next, we propose to utilize trace slicing to remove irrelevant activities from the IDG that do not impact the state mapping for instance migration. Based on the pruned instance dependence graph

(PIDG), we come up with a novel migration criterion (approach) for migration validity checking: if there exists a topological sort of activities in the PIDG such that it can be replayed in the new process version, the migration validity of the corresponding instance is satisfied. We also present detailed algorithms realized in our publicly available proof-of-concept tool Dilepis. An extensive experiment and an intensive case study are conducted, the results of which demonstrate that our approach can achieve an improved instance migration rate as compared to state-of-the-art approaches that are based on trace replaying. Additionally, the improvement of the migration rate does not significantly compromise the efficiency of our approach; specifically, our approach scales well with increasing process scale, trace length, and trace quantity, respectively.

Since our work only focuses on instance migration from the perspective of orchestration evolution, the next stage is to extend our approach for the dynamic evolution of data-aware choreographies, where environment properties, i.e., external services, need to be considered.

Acknowledgments

The authors are grateful to anonymous reviewers for their insightful and constructive comments. This work was supported in part by the National Key R&D Program of China under Grant No. 2017YFB1001801, the Natural Science Foundation of Jiangsu Province under Grant No. BK20171427, the Fundamental Research Funds for the Central Universities under Grant No. 30917011322, the China Scholarship Council under Grant No. 201606845006, NSERC, and the Alexander von Humboldt Foundation under Grant No. 5090551. The work was completed in parts at the University of Toronto, Canada and at the Technische Universität München, Germany. W. Song is the corresponding author of the article.

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