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Workflow modeling for virtual processes: an order-preserving process-view approach ☆

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Abstract

Conducting workflow management allows virtual enterprises to collaboratively manage business processes. Given the diverse requirements of the participants involved in a business process, providing various participants with adequate process information is critical to effective workflow management. This work describes a novel process-view, i.e., an *abstracted process* which is derived from a *base process* to provide process abstraction, for modeling a *virtual workflow process*. The proposed process-view model enhances the conventional activity-based process models by providing different participants with various views of a process. Moreover, this work presents a novel order-preserving approach to derive a process-view from a base process. The approach proposed herein can preserve the original ordering of activities in the base process. Additionally, a formal model is presented to define an order-preserving process-view. Finally, an algorithm is proposed for automatically generating an order-preserving process-view. The proposed approach increases the flexibility and functionality of workflow management systems.

Keywords: Workflow management; Process abstraction; Virtual workflow; Process modeling

1. Introduction

Workflow management via workflow management systems (WfMSs) not only facilitates electronic commerce, but also allows virtual enterprises to collaboratively manage business processes. As an effective process management tool, WfMSs allow businesses to analyze, simulate, design, enact, control and monitor their overall business processes [1,2]. The support of a WfMS allows various participants to collaborate in effectively managing a workflow-controlled business processes. The participants represent particular positions in a company or particular companies in a supply chain. In practice, these participants possess different needs and levels of authority when obtaining information on business processes. To facilitate effective workflow management, a WfMS should provide various participants with adequate process information.

For example, a high-level manager may require aggregated information on a process, while a marketing manager may not have the authority or need to know each specific step of the production flow. These requirements create the

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need for a flexible process model capable of providing appropriate processes abstraction for various roles within an enterprise. Furthermore, interorganizational coordination via WfMSs has become a critical success factor for businesses in rapidly fluctuating and complex business environments. Besides the interoperability issues of heterogeneous WfMSs, in a WfMS-supported supply chain (or called multi-enterprise process [3]), each participatory organization wants to conceal its own processes from other organizations, and different organizations require different supply chain information. In sum, providing aggregated information or encapsulating sensitive data requires the development of a workflow model capable of offering adequate *abstracted processes* for different levels, units, and organizations.

Despite notational differences, activity-based methodologies are extensively used process modeling techniques, and have been extensively adopted for commercial products, research projects, and standards, e.g., MQSeries Workflow [4], Ultimus [5], METEOR [6], and workflow management coalition (WfMC) process definition metamodel [7]. A typical activity-based approach designs a workflow though a top-down decomposition procedure. This stepwise refinement allows a modeler to define a process more easily and completely than do one-step approaches.

However, resultant layered process definitions do not always fit into an organizational hierarchy, despite providing several different levels of hierarchical abstraction. Therefore, hierarchically decomposing a process may not provide each organizational level with an appropriate view of that process. Despite forcing a process modeler to follow an organizational hierarchy while decomposing a process, different organizational units (divisions/companies) may have difficulties in obtaining adequate abstractions of the process/supply chain they participate in. The activity-based approach cannot adequately provide different participants with varied abstracted processes.

The activity-based approach should be enhanced to provide different process abstractions. Several formal process modeling techniques, including process algebras and Petri Nets [8–11], can provide process abstractions by renaming activities to silent activities that are not observable. Such abstraction is considered as *partial abstraction* since it provides partial observability of a process. Although useful in satisfying some of the needs of process abstractions, partial abstraction may be unable to adequately address the needs of managers or collaborative parties who require aggregated information on a process.

Based on the notion of views in database management systems (DBMSs), this work proposes a novel *virtual workflow process*, i.e., a *process-view*, in a WfMS. A process-view, i.e., an *abstracted process* derived from an implemented *base process*, is employed to provide *aggregate abstraction* of a process. During workflow build time, a process modeler does not need to be concerned with process abstraction, and can focus solely on process design, using a top-down decomposition procedure to define the process in detail. The modeler can then use a process-view definition tool to define multiple abstracted processes, i.e., process-views. During run time, creating a process instance initiates its corresponding process-view instances. Each participant can retrieve and monitor appropriate process information via the related process-view instance. Therefore, coordination within an organization or across multiple organizations can be improved.

Although process design is a specialized and top-down procedure, process-view design is a generalized and bottom-up procedure. Process-views allow a WfMS to provide various aggregated views of a process for different levels or departments in an organization or for different organizations in a supply chain. Several approaches can be adopted to construct a process-view. This work describes a novel order-preserving approach in which the constructed process-view can preserve the original ordering of activities in the base process. A formal model is also presented to define an order-preserving process-view. Theoretical analysis is performed herein, indicating that the defined process-view satisfies the order-preserving property. Moreover, an algorithm is proposed to automatically generate an order-preserving process-view.

The remainder of this paper is organized as follows. Section 2 formally defines business processes. Section 3 then describes and defines a process-view. Next, Section 4 presents the proposed order-preserving approach to construct a process-view. Section 5 then discusses and compares related work on workflow modeling. Conclusions and future work are finally made in Section 6. Appendix A provides proofs of all lemmas.

2. Workflow model: a base process

A process that may have multiple process-views is termed a *base process* herein. Activity-based workflow models generally use *activities* and *dependencies* to describe a process. Dependencies prescribe the ordering relationships between activities within a process. According to WfMC [7], the following six ordering structures may appear in business processes. *Sequence*: An activity has a single subsequent activity. *AND-SPLIT*: An activity splits into multiple parallel activities that are all executed. *XOR-SPLIT*: An activity splits into multiple mutually exclusive alternative activities, only one of which is followed. *AND-JOIN*: Multiple parallel executing activities join into a single activity. *XOR-JOIN*: Multiple mutually exclusive alternative activities join into a single activity. *Loop*: One or more activities are repeatedly executed until the exit condition is satisfied.

The above ordering constructs are not arbitrarily combined. For example, AND-SPLIT must pair with AND-JOIN, and XOR-SPLIT must pair with XOR-JOIN. Wrong combinations of ordering structures may cause structural conflicts such as deadlock and non-reachability. Verification issues are beyond the scope of this work. Please refer to Woflan [12] and FlowMake [13] to verify the correctness of process definitions. This work assumes that the given process definitions are structurally correct.

Moreover, a well-structured loop in a process definition should have a single entry and a single exit, as the iteration statements in programming languages. Allowing multiple entries/exits makes the complex control flow hard to understand, and induces ambiguities in the evaluation of exit conditions. Leymann et al. [14] also claim that race conditions may occur in arbitrary loops. Thus, this work prescribes that a loop must be single-entry and single-exit.

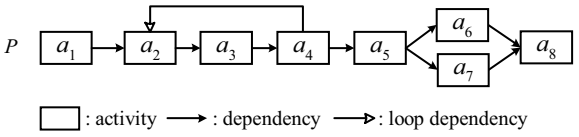


Fig. 1. Sample process.

A graphical representation of a process resembles a *directed graph* [15] in which each node is an activity and each directed edge is a dependency. This work uses a rectangle to denote an activity and a solid arrow to represent a dependency in a process graph. Moreover, a blank arrow indicates a loop dependency used to construct a loop structure. Fig. 1 depicts a sample process. A loop dependency from a_4 to a_2 indicates that activities a_2, a_3 , and a_4 form a loop in which a_2 is the entry point and a_4 is the exit point. The single-entry loop is converted into a multi-entry loop, for example, by adding a dependency from a_1 to a_3.

2.1. Formal model

To elucidate the derivation of process-views from base processes, a formal model is introduced first for describing base processes. The model is revised from the standard WfMC process definition language [7] and focuses only on activities and dependencies to simplify the discussion.

Definition 1 (Process and sub-process). A process P is a 2-tuple $\langle A, D \rangle$, where A is a set of activities and D is a set of dependencies and loop dependencies. A process $P' = \langle A', D' \rangle$ is a *sub-process* of P if $A' \subseteq A$ and $D' \subseteq D$.

Definition 2 (Dependency). A dependency is a 4-tuple $\langle$activity x, activity y, type R, condition $C\rangle$, denoted by $dep(x, y, R, C)$, where x, $y \in A$. Condition C represents the constraints that determine whether routing can proceed from x to y. The dependency $dep(x, y, R, C)$ is an *outgoing* dependency of x and an *incoming* dependency of y.

Activity x is called the *preceding* activity and y is called the *succeeding* activity in $dep(x, y, R, C)$. Type R indicates that $dep(x, y, R, C)$ is not a loop dependency.

Definition 3 (Loop dependency and loop). A loop dependency is a 4-tuple $\langle$activity ex, activity ei, type L, loop condition $LC\rangle$, denoted by $dep(ex, ei, L, LC)$, where ex, $ei \in A$. Type L refers to a loop dependency. Additionally, $dep(ex, ei, L, LC)$ implies that there exists a *loop*, denoted by $lp(ei, ex) = \langle A_{lp(ei,ex)}, D_{lp(ei,ex)}\rangle$, where $A_{lp(ei,ex)} = \{ei, ex,$ and all activities between ei and $ex\}$, and $D_{lp(ei,ex)} = \{dep(x, y, R, C_{xy})$ or $dep(x, y, L, LC_{xy})$ $|x, y \in A_{lp(ei,ex)}\}$; ei is the entry point and ex is the exit point. Notably, a loop is here restricted to having one entry and one exit point. All activities of $A_{lp(ei,ex)}$ are repeatedly executed until LC is evaluated as false.

Definition 4 (Activity). An activity ba is a 3-tuple $\langle SPLIT\_flag, JOIN\_flag, SC\rangle$, where

1. *SPLIT_flag* may be "NULL", "AND", or "XOR". "NULL" means that ba has a single outgoing dependency (Sequence). "AND" means that ba has multiple outgoing dependencies labeled with identical conditions (AND-SPLIT). "XOR" means that ba has multiple outgoing dependencies associated with mutually exclusive conditions (XOR-SPLIT).
2. *JOIN_flag* may be "NULL", "AND", or "XOR", and is used to derive SC. "NULL" indicates that this activity has a single incoming dependency (Sequence). Given multiple incoming dependencies, "AND" indicates that ba can be started if the conditions of all incoming dependencies are satisfied (AND-JOIN), while "XOR" indicates that ba can be started if one of its incoming dependencies has satisfied conditions and the others are associated with unsatisfied conditions (XOR-JOIN).
3. SC is the *starting condition* of ba. SC explicitly expresses the condition whether ba can be started, and is derived from the *JOIN_flag* and the condition fields of incoming dependencies. First, if *JOIN_flag* is NULL, SC equals the condition (C) of the incoming dependency. Secondly, if *JOIN_flag* is XOR, SC equals the Boolean XOR combination of the conditions of all incoming dependencies. Finally, if *JOIN_flag* is AND, SC equals the Boolean AND combination of the conditions of all incoming dependencies.

Enacting a process. During run-time, an execution of a process is called a *process instance*. For $dep(x, y, R, C)$, C is not evaluated until x is completed. The evaluation of C is either true or false. The fact that x is completed and C is evaluated as true is one precondition that determines whether y can be started. For convenience, "a dependency is evaluated as true/false" states that the dependency's condition field is evaluated as true/false.

The SC field of an activity ba is evaluated when all incoming dependencies of ba have been evaluated. ba can be started when SC is evaluated as true. Note that SC is derived from the *JOIN_flag* and the condition fields of ba's incoming dependencies. If ba is started, then its outgoing dependencies are evaluated after the completion of ba. If SC is evaluated as false, then ba is not executed in the process instance, and the outgoing dependencies of ba are evaluated as false.

An activity is called a *fired* activity in a process instance if its SC is evaluated as true and it is executed in the process instance. Moreover, an activity is called a *non-fired* activity in a process instance if its SC is evaluated as false and it is not executed in the process instance. Notably, an activity that is non-fired in a process instance may be fired in other process instances. For convenience, "an activity is evaluated as fired/non-fired" states that the activity's SC is evaluated as true/false.

For $dep(ex, ei, L, LC)$, after ex is completed, LC is (re)evaluated to decide whether the loop $lp(ei, ex)$ is repeated. If LC is evaluated as true, then $lp(ei, ex)$ is repeated. Notably, each execution of $lp(ei, ex)$ starts a new *iteration* and initiates a new execution context of $lp(ei, ex)$. The activities and (loop) dependencies of $lp(ei, ex)$ are reset for re-execution and re-evaluation when a new iteration of $lp(ei, ex)$ is started. Thus, the activities and (loop) dependencies within a new iteration are

initially non-evaluated. The activities of $lp(ei, ex)$ are re-evaluated as fired/non-fired in an iteration of $lp(ei, ex)$. Additionally, the completion of an activity that belongs to $lp(ei, ex)$ means that the activity is completed in an iteration of $lp(ei, ex)$. The activity may be started/completed again in the follow-on iterations of $lp(ei, ex)$. Besides, the completion of $lp(ei, ex)$ means that the entire loop stops; that is, LC is evaluated as false and $lp(ei, ex)$ is not repeated. The starting of $lp(ei, ex)$ means the starting of ei in the first iteration of $lp(ei, ex)$. Notably, where $lp(ei, ex)$ is a nested loop if it belongs to another loop which is called the *outer* loop. For the two levels of nesting, the above is also applied to each iteration of the outer loop. Furthermore, the above can be recursively applied to the case of more than two levels of nesting.

If a process contains loops, then two revisions are needed for the entry and exit points of those loops. (1) For $dep(x, y, R, C)$, if x is the exit point of a loop (i.e., x is also associated with a loop dependency), then C is evaluated when x is completed and the loop condition is evaluated as false (i.e., the loop stops). Moreover, if x is evaluated as non-fired, then C and the loop condition are evaluated as false. (2) For an activity *ba*, if *ba* is the entry point of a loop, then whether *ba* can be started depends on both SC and the loop condition. In the first iteration of the loop, *ba* is started/fired if SC is evaluated as true. In the follow-on iteration(s), *ba* is started/fired if the loop condition is evaluated as true (i.e., the loop is repeated).

For convenience, in the rest of this work, $dep(x, y, \_, \_)$ indicates a situation in which type and condition field are free.

Definition 5 (Adjacent). Two distinct activities x and y are *adjacent* if $dep(x, y, \_, \_)$ exists.

Definition 6 (Path). A path of length k from an activity x to an activity y in a process $P = \langle A, D \rangle$ is a sequence of activities $a_0, a_1, \ldots, a_k$ such that $x = a_0$, $y = a_k$, and $dep(a_{i-1}, a_i, \_, \_) \in D$ for $i = 1, 2, \ldots, k$. The length of the path is the number of (loop) dependencies on the path. The path contains the activities $a_0, a_1, \ldots, a_k$ and the (loop) dependencies $dep(a_{i-1}, a_i, \_, \_)$ for $i = 1, 2, \ldots, k$.

Definition 7 (Loop-derived sub-process). Given a process $P = \langle A, D \rangle$, if $dep(ex, ei, L, LC)$ exists in P, then a loop $lp(ei, ex)$ exists in P. A sub-process can be derived by excluding $dep(ex, ei, L, LC)$ from $lp(ei, ex)$. That is, for $lp(ei, ex)$ in P, a sub-process $LP(ei, ex) = \langle A_{LP(ei,ex)}, D_{LP(ei,ex)} \rangle$ where $A_{LP(ei,ex)} = \{x | x \text{ belongs to } lp(ei, ex)\}$, and $D_{LP(ei,ex)} = \{dep(x, y, \_, \_) | x, y \in A_{LP(ei,ex)}\} - \{dep(ex, ei, L, LC)\}$. $lp(ei, ex)$ can be viewed as a repeatedly executed $LP(ei, ex)$. $LP(ei, ex)$ is called a *loop-derived* sub-process that is derived from $lp(ei, ex)$.

To clarify the target for discussion, *lp* and *LP* are used in parts of this work to denote a loop and a loop-derived sub-process, respectively.

Definition 8 (Ordering relation). Given a process $P = \langle A, D \rangle$ and a sub-process $P' = \langle A', D' \rangle$ of P, the ordering relation between an activity x and an activity y in P' is defined as follows:

1. If there exists a path from x to y in P', then the ordering of x is higher than y, i.e., x precedes y. Their ordering relation is denoted by $x > y$ or $y < x$ which means $x > y$ (or $y < x$) holds in P'.
2. If no path exists from x to y or from y to x in P', then x and y are ordering independent, i.e., x and y proceed independently. Their ordering relation is denoted by $x \infty y$ which means $x \infty y$ holds in P'.

Definition 8.1 implies that if another activity $z \in A'$ exists, such that $x > y$ and $y > z$ hold in P', then $x > z$ holds in P'. Notably, the ordering relations may hold in P but do not hold in the sub-processes. For example, in Fig. 1, the ordering relations among a_2, a_3, and a_4 in P are $a_2 > a_3$, $a_2 < a_3$, $a_2 > a_4$, $a_2 < a_4$, $a_3 > a_4$, and $a_3 < a_4$ because the ordering relations can be derived from the paths that include $dep(a_4, a_2, L, LC_{42})$. However, only the ordering relations $a_2 > a_3$, $a_2 > a_4$, and $a_3 > a_4$ hold in $LP(a_2, a_4)$, derived from $lp(a_2, a_4)$, because the ordering relations are derived from the paths that exclude $dep(a_4, a_2, L, LC_{42})$. The semantics of "$a_2 < a_3$ holds in P" can be elucidated as a_3 is executed in the iteration of $lp(a_2, a_4)$ before a_2 is executed in the follow-on iteration of $lp(a_2, a_4)$ in an instance of P. The semantics of "$a_2 > a_3$ holds in $LP(a_2, a_4)$" is elucidated as a_2 is executed before a_3 in each iteration of $lp(a_2, a_4)$.

3. Virtual process: a process-view

Views in DBMSs are virtual tables generated from either physical tables or previously defined views. Similarly, process-views are generated from either physical processes (base processes) or other process-views, and are considered *virtual processes*. During design time, a process modeler defines various process-views based on the roles of participants. During run time, a WfMS initiates all process-view instances if their base process is initiated. Process-views allow a process modeler to flexibly provide different roles (i.e., different levels or departments within an organization or different organizations in a supply chain) with appropriate views of an implemented process. This ability implies that a modeler can provide only the information that participants need to know, while filtering and concealing information as desired. Fig. 2 illustrates this concept.

Assume that the base process in Fig. 2 is a manufacturing process. Marketers do not need to know every step in the process, although they must know the progress of order fulfillment to serve their customers. A process modeler can design an appropriate process-view for the marketing department as follows: a_1, a_2, and a_3 are mapped into va_1; a_4 and a_5 are mapped into va_2; a_6 and a_7 are mapped into va_3. When a customer places a new order, the WfMS initiates a new manufacturing process instance and corresponding process-view instances. Marketers can use the information from the process-view instance to serve customers. A case study in Section 4.4 demonstrates more applications of process-views.

Like process design, the design of a process-view must first identify any activities within it and then arrange them based on dependencies and ordering structures. However, an "activity" in a process-view is not performed, but rather is used to express the progress information of a set of activities. Hence, to differentiate the terminology used in base process and process-view, this work uses the terms *virtual activity* and *virtual* (*loop*) *dependency* for the process-view, and the terms *base activity* and *base* (*loop*) *dependency* for the base process. While a virtual activity is derived from a bottom-up aggregation of a set of activities within a process, a base activity is generated from a top-down decomposition of a business process. A process modeler develops a process definition and then defines process-views.

3.1. Formal model

Definition 9. (Process-view). A process-view VP is a 2-tuple $\langle VA, VD \rangle$, where VA is a set of virtual activities and VD is a set of virtual dependencies and virtual loop dependencies. During run-time, an execution of a process-view is called a *process-view instance*.

A process-view has a *corresponding* base process from which it is derived. A virtual activity is an abstraction of a set of base activities and correlative base (loop) dependencies. A virtual dependency connects two virtual activities in a process-view, and a virtual loop dependency constructs a loop structure in a process-view.

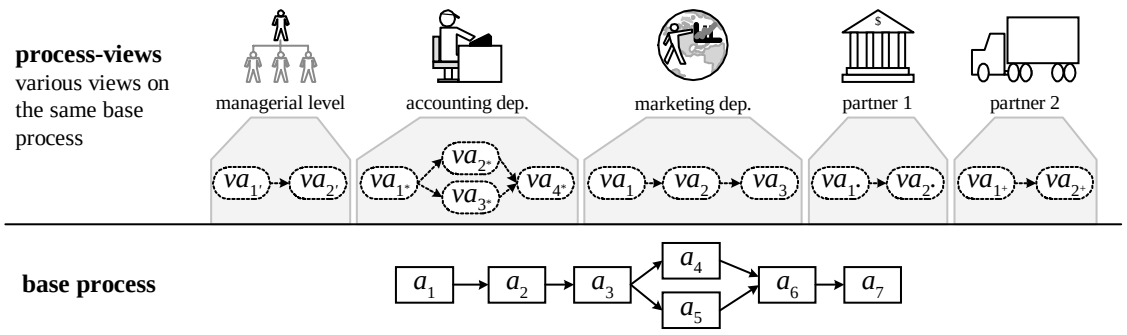


Fig. 2. Illustrative examples of process-views.

According to the different properties of a base process, various approaches can be developed to derive *VA* and *VD*. Section 4 presents an approach that preserves the original execution order of a base process.

Regardless of how *VA* and *VD* are derived, the definitions of *path*, *loop* (denoted by *vlp*(_, _)), *loop-derived sub-process-view* (denoted by *VLP*(_, _)) and *ordering relations* for a process-view are similar to Definitions 3, 6, 7 and 8. For example, the definition of "path" for a process-view can be obtained by replacing "activity/(loop) dependency/process" in Definition 6 with "virtual activity/virtual (loop) dependency/process-view". Therefore, those definitions are omitted herein for brevity.

Fig. 3 illustrates the relationship between the components of the novel model. *Base process relevant data* defines the data created and used within each process instance during workflow enactment [7]. Similarly, the produced and consumed data of a process-view is termed *process-view relevant data*. Since a virtual activity is an abstraction of a set of base activities, the produced/consumed data of a virtual activity is the set of data that is produced/consumed by the base activities belonging to the virtual activity.

4. Order-preserving approach

Execution order is an important property of business processes, particularly continuous manufacturing processes such as chemical materials, integrated circuit (IC), and steel. This section first introduces three rules that a process-view must follow to preserve the ordering property. Then virtual activities and (loop) dependencies in an order-preserving process-view are formally defined based on these rules. *Essential activities*, i.e., activities that a modeler wants to conceal or aggregate in a virtual activity, are proposed to simplify the procedure of defining a virtual activity. Next, a liquid crystal display (LCD) production flow is used to illustrate the application of process-views. Finally, novel algorithms that automatically generate legal virtual activities and virtual (loop) dependencies are also proposed herein.

4.1. Basic rules

The following introduces three rules for defining virtual activities.

4.1.1. Rule 1 membership

A virtual activity can be viewed as a set of activities of a base process. Restated, a virtual activity comprises base activities. For further abstraction, a virtual activity may comprise other previously defined virtual activities. As illustrated in Fig. 4, member activities of a virtual activity may include base activities, virtual activities, or both. The membership among base activities and virtual activities is defined transitively. That is, if a base activity *ba* is a member of a virtual activity

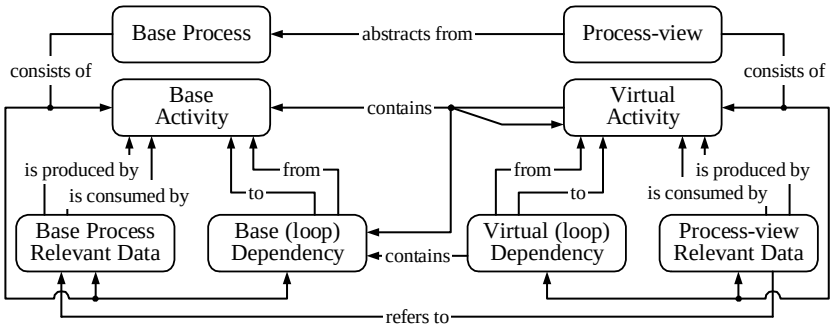


Fig. 3. Process-view model.

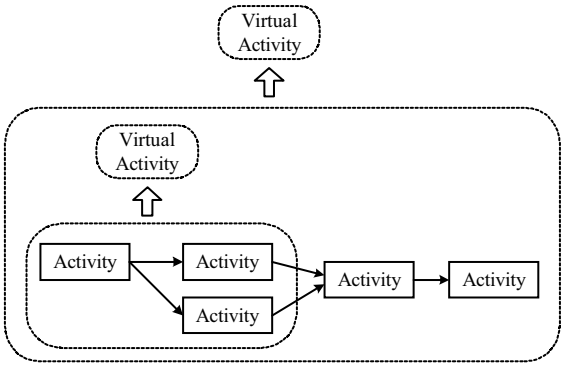


Fig. 4. Illustrative examples of virtual activities' members.

va_1, and va_1 is a member of another virtual activity va_2, then ba is also a member of va_2.

4.1.2. Rule 2 atomicity

A virtual activity is an atomic unit of processing. The following first considers the case of base processes that do not contain loops to explain clearly the atomicity rule. Notably, a virtual activity may contain other virtual activities according to the membership rule. The behavior of a virtual activity is determined by its member base activities since base activities are the actual execution units. For example, if va_1 contains va_2 and ba_1, and va_2 contains ba_2 and ba_3, then member base activities of va_1 are ba_1, ba_2, and ba_3.

In a base process, each base activity is executed atomically; that is, the starting of a base activity implies all its preceding base activities have been evaluated and the fired ones are completed in the base process instance. Thus, the claim that "each virtual activity proceeds atomically in a process-view" rests on three requirements.

1. A virtual activity is started if one member base activity is started, and is completed if all member base activities have been evaluated and each fired member base activity is completed.
2. In a process-view instance, a virtual activity is evaluated as fired if one member base activity is evaluated as fired, and is evaluated as non-fired if all member base activities are evaluated as non-fired.
3. The starting of a virtual activity implies that all its preceding virtual activities have been evaluated and each preceding fired virtual activity is completed in the process-view instance.

Requirements 1 and 2 describe how to decide the behavior of a virtual activity, and requirement 3 specifies the behavior of a process-view. Each virtual activity is an indivisible unit in a process-view, and, thus, can be decided as started if one member base activity is started. As stated in Section 2.1 (enacting a process), whether a base activity is either fired or non-fired in a base process instance is unknown until the *SC* of the base activity has been evaluated. Consequently, a virtual activity can be decided as completed when the starting condition of each member base activity has been evaluated and each fired member base activity is completed. Moreover, the starting of a virtual activity occurs after the completion of its preceding fired virtual activities in a process-view instance.

Consider three process-views VP_a, VP_b, and VP_c as shown in Fig. 5 where each virtual activity follows requirements 1 and 2. When a_3 is started, a_1 and a_2 should be completed in the base process. Under such conditions, three process-views behave differently from each other. In VP_a, va_2 is started (because a_3 is started) and va_1 has been completed. This behavior follows atomicity property. Contrarily, in VP_b, va_1 is not completed since whether a_4 is fired is currently unknown, i.e., the starting condition of a_4 is not yet evaluated. Meanwhile, va_2 is completed and va_3 is started. Restated, the current status is that va_1 is started, va_2 is completed, and va_3 is started. This behavior is incompatible with the ordering relations of VP_b. Therefore, VP_b violates the atomicity property since it does not satisfy requirement 3. The behavior of VP_c is similar to that of VP_b. However, va_1 of VP_b cannot be decided as completed until the end of the base process instance, while va_1 of VP_c can be decided as completed when a_3 is completed. Notably, the virtual activities defined in VP_d are identical to those defined in VP_c. However, these activities have different ordering relations. VP_d also violates

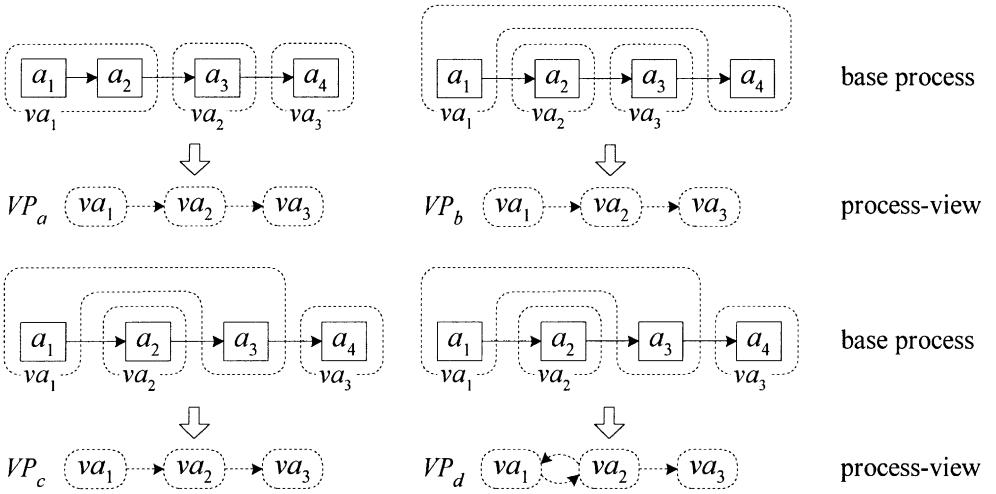


Fig. 5. Illustrative examples of the atomicity property.

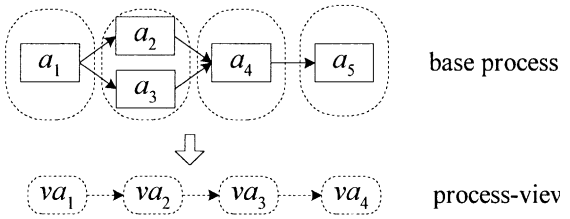


Fig. 6. Illustrative example of atomicity in the split structure.

the atomicity property because va_1 is not completed when va_2 is started.

As another example, in Fig. 6, the starting of virtual activity va_3 implies that va_2 is completed since $va_2 > va_3$. If the *SPLIT_ flag* of a_1 is AND and the *JOIN_ flag* of a_4 is AND, then a_4 cannot be started until a_2 and a_3 are completed. The completion of va_2 implies that a_2 and a_3 are completed. However, if the *SPLIT_ flag* of a_1 is XOR and the *JOIN_ flag* of a_4 is XOR, then a_4 cannot be started until a_2 or a_3 are completed. The completion of va_2 implies that either a_2 or a_3 is completed, while the other is non-fired in the base process instance.

Base processes that contain loops. The repeatable property distinguishes the base activities that belong to a loop from the other ones. The operational semantics of a virtual activity should not infer a new repeatable behavior that does not occur in the base process since a virtual activity is only an abstraction of a set of base activities. Restated, although capable of concealing and revealing original behavior, an abstraction should not imply new behavior. Hence, four cases are possible to define a virtual activity with respect to a loop *lp* of a base process. First, the virtual activity does not contain base activities that belong to *lp*. Second, the virtual activity contains the entire *lp*. Third, the virtual activity only contains partial base activities of *lp*. Fourth, the virtual activity contains not only partial (not all) base activities of *lp*, but also some base activities that do not belong to *lp*.

The second definition, although concealing the repeatable behavior, does not infer new one, even if it contains the entire *lp* and some base activities that do not belong to *lp*. Regarding the fourth definition, the repeatable behavior of the virtual activity corresponds to the repeated execution of *lp*. Such repeatable behavior implies that the base activities that do not belong to *lp* are also involved in the repeatable semantics of *lp* since a virtual activity is an atomic unit. Hence, the fourth definition imposes repeatable semantics on the base activities that do not belong to *lp*, and is not a reasonable abstraction.

The above atomicity requirements are extended to tackle the base process that contains loops, and are summarized below. For clarity, the following

describes the case of base processes that do not have nested loops. However, this rule can be recursively applied to handle nested loops.

Summary of atomicity rule. Four cases are possible to define a virtual activity *va* with respect to a loop *lp* in the base process.

Case 1: *va* does not contain base activities that belong to *lp*.

Case 2: *va* contains the whole *lp*. The whole *lp* is viewed as a member base activity; it is started when *lp* starts and is completed when *lp* stops; it is evaluated as fired/non-fired if the *SC* of the entry point of *lp* is evaluated as true/false.

1. *va* is started if one member base activity is started, and is completed if all member base activities have been evaluated and each fired member base activity is completed.
2. In a process-view instance, *va* is evaluated as fired if one member base activity is evaluated as fired, and is evaluated as non-fired if all member base activities are evaluated as non-fired.
3. The starting of *va* implies that all its preceding virtual activities have been evaluated and each preceding fired virtual activity is completed in the process-view instance.

Case 3: *va* only contains partial base activities of *lp* in the base process; accordingly, *va* belongs to a loop *vlp* in the process-view. A correspondence exists between *vlp* and *lp*, just as a process-view has a corresponding base process. The completion of *va* that belongs to *vlp* means that *va* is completed in an iteration of *vlp* in the process-view instance; *va* may be started/completed again in the follow-on iterations of *vlp* in the process-view instance. Similarly, the completion of member base activities means that these base activities are completed in an iteration of *lp* in the base process instance. Member base activities may be started/completed again in the follow-on iterations of *lp* in the base process instance.

1. Starting and completion of *va*:
   - *Starting*: *va* is started in an iteration of *vlp* in the process-view instance if one member base activity is started in an iteration of *lp* in the base process instance.
   - *Completion*: *va* is completed in an iteration of *vlp* in the process-view instance if all member base activities have been evaluated and each fired member base activity is completed in an iteration of *lp* in the base process instance.
2. In an iteration of *vlp* in the process-view instance, *va* is evaluated as fired if one member base activity is evaluated as fired in an iteration of *lp* in the base process instance, and is evaluated as non-fired if all member base activities are evaluated as non-fired in an iteration of *lp* in the base process instance.
3. In an iteration of *vlp* in the process-view instance, the starting of *va* implies that all its preceding virtual activities have been evaluated and each preceding fired virtual activity is completed.

Case 4: *va* cannot be defined as the case that contains not only partial (not all) base activities of *lp*, but also some base activities that do not belong to *lp*.

Discussion. In case 2, a virtual activity encapsulates a whole loop, thus it is reasonable to view the loop as a member activity. That is, the behavior of repeated execution of the loop is hidden by the virtual activity. Therefore, the completion of the member activity refers to the completion of the whole loop; that is, the end of the cyclic execution of the loop. However, a virtual activity in case 3 does not hide a whole loop. Hence, the virtual activity must reveal that its member activities are repeatedly executed. That is, repeatable behavior should be preserved. Accordingly, in case 3, the process-view must contain a loop that corresponds to the loop of the base process. That is, member base activities of the virtual activities that belong to *vlp*, must belong to *lp*. On the other hand, if a loop exists in the process-view, then a corresponding loop can be found in the base process.

Consider the two process-views VP_a and VP_b as shown in Fig. 7. Case 1 determines the behavior of va_1 and va_3 in VP_a. Similarly, case 1 determines the behavior of va_1 and va_4 in VP_b. However, the behavior of va_2 in VP_a is determined by case 2 since va_2 contains a whole loop $lp(a_2, a_4)$. In VP_a, va_2 is started if a_2 is started, and it is completed

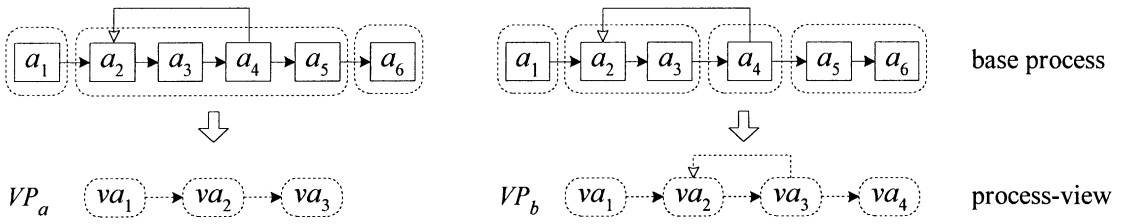


Fig. 7. Illustrative examples of atomicity in the loop structure.

when $lp(a_2, a_4)$ stops and a_5 is completed. As to VP_b, case 3 determines the behavior of va_2 and va_3. Completion of va_2 in an iteration of the loop $vlp(va_2, va_3)$ in VP_b means a_2 and a_3 are completed in one iteration of the loop $lp(a_2, a_4)$ in the base process instance. In the follow-on iteration(s), va_2 is started/completed again. Notably, $vlp(va_2, va_3)$ of VP_b corresponds to $lp(a_2, a_4)$ of the base process.

4.1.3. Rule 3 order preservation

Briefly, this rule states that a process-view must preserve the original ordering relations of a base process. Order preservation provides a syntactical constraint that ensures that a process-view follows the atomicity property. The following first explains order preservation and then summarizes this rule.

A situation in which the ordering relation between two virtual activities is "$>$" in a process-view infers that the *implied* ordering relation between the respective members of these virtual activities is "$>$" due to the atomicity property of virtual activity. Corresponding inferences also hold for the ordering relations "$<$" and "∞", respectively. For example, the process-view in Fig. 6 shows that the ordering relation between va_1 and va_2 is $va_1 > va_2$. "$va_1 > va_2$" infers that "$>$" is the implied ordering relation between any member of va_1 and any member of va_2 because a virtual activity is an atomic unit; that is, $va_1 > va_2$ implies $a_1 > a_2$ and $a_1 > a_3$. Notably, the implied ordering relations may not conform to the ordering relations of the base process; that is, the implied ordering relations may not hold in the base process.

Consider the base process depicted in Fig. 8(a), which seeks to define a virtual activity that must contain activities a_{11} and a_{22}. Figs. 8(b) and (c) provide two possible definitions. In the base process, three branches proceed independently and autonomously, while the ordering relation between a_{13} and a_{22} is $a_{13} \infty a_{22}$. However, if a virtual activity is defined as in Fig. 8(b), then a_{11}, a_{12}, a_{21}, and a_{22} are viewed as an atomic unit since they are members of the same virtual activity. The ordering relation *virtual activity* $> a_{13}$ infers an implied ordering relation $a_{22} > a_{13}$. This implied ordering relation does not hold in the base process. Hence, the virtual activity must contain all activities in *branches* 1 and 2, as shown in Fig. 8(c), to preserve the original ordering relations.

The implied ordering relation $a_{22} > a_{13}$ means that a_{13} must wait for the completion of a_{22} before it can start. Perhaps a_{13} is started after a_{11}, a_{12}, a_{21}, and a_{22} are completed in the base process instance. In this situation, the virtual activity defined in Fig. 8(b) satisfies the atomicity property. However, such a definition cannot assure the atomicity property; that is, the property may not hold for the other base process instances. If implied ordering relations conform to the original ordering relations, then the progress expressed in virtual activities necessarily satisfies the atomicity property.

The definition of a virtual activity must maintain repetitive execution order of a loop structure. In Fig. 9, for example, each numbered dotted rectangle is a possible virtual activity definition. While alternatives 1 and 2 are valid, alternatives 3 and 4 alter the original ordering relations. Alternative 3 creates an implied ordering relation $a_3 > a_1$; that is, a_1, a_2, and a_3 may be executed repetitively (a_1 and a_2 are viewed as an atomic unit). Likewise, alternative 4 creates an implied ordering relation $a_4 > a_2$; that is, a_4 may be executed before the condition that a_2 and a_3 be repetitively executed, is satisfied.

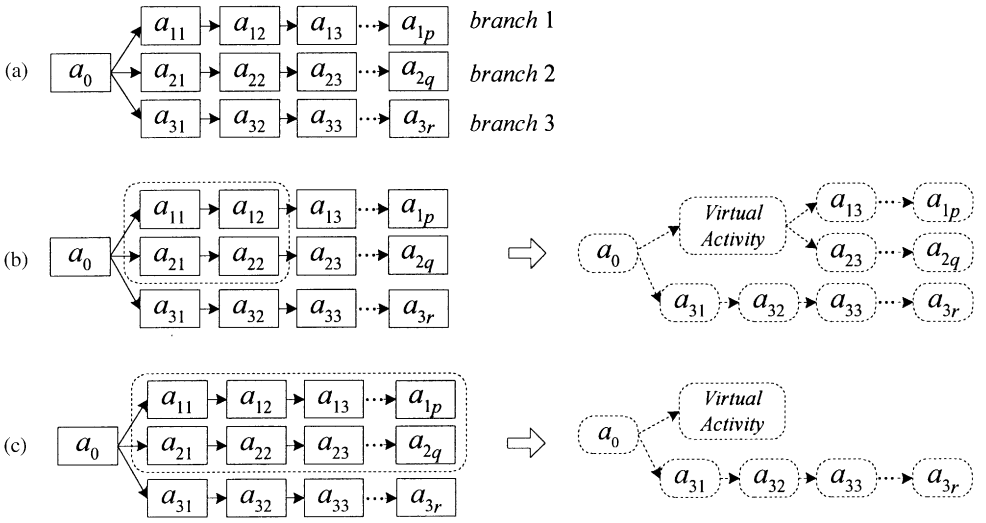


Fig. 8. Illustrative examples of order preservation in the split structure.

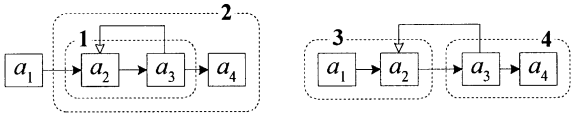


Fig. 9. Illustrative examples of order preservation in the loop structure.

Fig. 10 seems to show a valid process-view definition because implied ordering relations derived from *VP* can be found in *BP*. However, the loop-derived sub-process-view $VLP(va_2, va_3)$ does not preserve the ordering relations of the loop-derived sub-process $LP(a_2, a_5)$. When a_2 is completed and a_3 is started in the iteration of $lp(a_2, a_5)$, va_2 is not completed (because whether a_4 is fired is currently unknown) and va_3 is started in the iteration of $vlp(va_2, va_3)$. Atomicity is violated in this situation. The process-view must contain a loop structure that corresponds to the loop of the base process when a virtual activity of a process-view does not hide an entire loop of a base process, as stated in the atomicity rule. In such situations, to keep the atomicity property, the loop-derived sub-process-view must preserve the ordering relations of the corresponding loop-derived sub-process.

In Fig. 10, $a_2 > a_3$, $a_3 > a_4$ and $a_4 > a_5$ hold in $LP(a_2, a_5)$. However, "$va_2 > va_3$ holds in $VLP(va_2, va_3)$" implies that $a_2 > a_3$, $a_4 > a_3$, $a_2 > a_5$, and $a_4 > a_5$. The implied ordering relation "$a_4 > a_3$" does not hold in $LP(a_2, a_5)$. Therefore, $VLP(va_2, va_3)$ does not preserve the ordering relations of $LP(a_2, a_5)$.

Summary of order preservation rule. If the ordering relation between two virtual activities is "$>$" in a process-view/loop-derived sub-process-view, then the *implied* ordering relation between the respective members of these virtual activities is also "$>$". Corresponding inferences also hold for the ordering relations "$<$" and "∞", respectively. The implied ordering relations between the respective members of two virtual activities must hold in the corresponding base process/loop-derived sub-process.

Restated, (1) Given a process-view *VP*, derived from a base process *BP*, for any two virtual activities va_i and va_j in *VP*: "$va_i > va_j$ holds in *VP*" implies that "$a_x > a_y$" for all a_x contained by va_i and all a_y contained by va_j; moreover, "$a_x > a_y$" must hold in *BP* for all a_x contained by va_i and all a_y contained by va_j. (2) Given a loop-derived sub-process-view *VLP*, derived from the corresponding loop-derived sub-process *LP*, for any two virtual activities va_i and va_j in *VLP*: "$va_i > va_j$ holds in *VLP*" implies that "$a_x > a_y$" for all a_x contained by va_i and all a_y contained by va_j; moreover, "$a_x > a_y$" must hold in *LP* for all a_x contained by va_i and all a_y contained by va_j. (3)

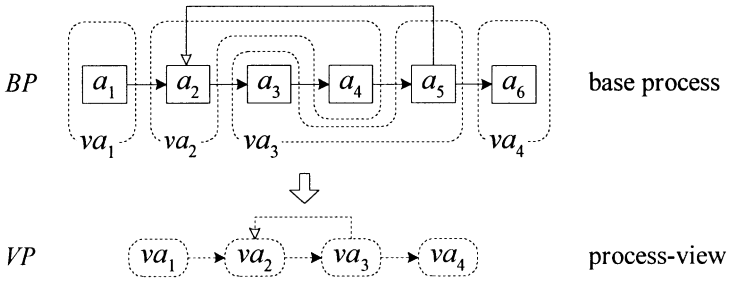


Fig. 10. Illustrative example of order preservation in the loop structure.

Statements (1) and (2) also hold for the ordering relations "$<$" and "∞", respectively.

Discussion. The atomicity rule describes the operational semantic property of a process-view. The order preservation rule provides a syntactical constraint that ensures a process-view follows the atomicity property. This approach is called *order-preserving* because implied ordering relations, derived from a process-view/loop-derived sub-process-view, conform to the ordering relations of the base process/loop-derived sub-process. A *legal* virtual activity in an order-preserving process-view must follow above three rules. Therefore, the behavior of a process-view whose virtual activities are legal can be determined by the behavior of its base process.

Consider a situation in which a member activity *ba* of a virtual activity *va* is started. Therefore, *va* is started. The following elucidates that the preceding fired virtual activities of *va* are completed in a process-view of which each virtual activity follows the above three rules. Consider any fired virtual activity va' with a higher order than *va* in the process-view. According to the order preservation rule, all member base activities of va' must have a higher order than *ba* since $va' > va$. In the base process, all base activities that precede *ba* have been evaluated and the fired ones are completed before *ba* is started since base activities are executed atomically. Thus, in the process-view, any virtual activity with a higher order than *va* can be determined as completed before *ba* is started because all of its fired member activities have been completed.

Contrarily, the starting of a member activity of an arbitrarily defined virtual activity that violates order preservation, cannot ensure that preceding virtual activities have been completed. Consider the same situation in which a member activity *ba* of a virtual activity *va* is started. The preceding virtual activities that violate order preservation contain some member base activities that do not have a higher order than *ba*. In the base process, all base activities with a higher order than *ba* are completed. However, base activities without a higher order than *ba* may be neither completed nor evaluated. Consequently, in the process-view, the virtual activities with higher order than *va* cannot be decided as completed because some of their member activities may not be completed before the starting of *ba*. Several virtual activities that are not ordering independent may be executed concurrently. The operational semantics of such a process-view violates the atomicity rule.

4.2. Formal model

The rules that a process-view should comply with have been introduced above. In the following, virtual activities and virtual (loop) dependencies in an order-preserving process-view are formally defined.

Definition 10 (Virtual activity). Given a base process $BP = \langle BA, BD \rangle$, a virtual activity *va* is a 5-tuple $\langle A, D, SPLIT\_flag, JOIN\_flag, SC \rangle$, where

1. A is a non-empty set, and its members follow three rules:
   (a) Members of A are base activities that are members of BA or other previously defined virtual activities that are derived from BP.

(b) The starting and completion of *va* are determined by the starting and completion of members of A, according to the atomicity rule.
(c) Let $BP' = \langle BA', BD' \rangle$ be BP or any loop-derived sub-process $LP(ei, ex)$ where $ei, ex \in BA$. For any $x \in BA'$ and $x \notin A$: if there exists a $y \in A$ and $y \in BA'$ such that $x > y$ holds in BP', then $x > z$ holds in BP' for all $z \in A$ and $z \in BA'$; if there exists a $y \in A$ and $y \in BA'$ such that $x < y$ holds in BP', then $x < z$ holds in BP' for all $z \in A$ and $z \in BA'$; if there exists a $y \in A$ and $y \in BA'$ such that $x \infty y$ holds in BP', then $x \infty z$ holds in BP' for all $z \in A$ and $z \in BA'$. That means the ordering relations between x and all members (base activities) of A that belong to BP' are identical.

2. $D = \{dep(x, y, \_, \_) | x, \ y \in A$ and $dep(x, y, \_, \_) \in BD\}$.
3. *SPLIT_flag* may be "NULL" or "MIX". NULL suggests that *va* has a single outgoing virtual dependency while MIX indicates that *va* has multiple outgoing virtual dependencies.
4. *JOIN_ flag* may be "NULL" or "MIX". NULL suggests that *va* has a single incoming virtual dependency while MIX indicates that *va* has multiple incoming virtual dependencies.
5. *SC* is the *starting condition* of *va*.

The *SPLIT_ flag* and *JOIN_ flag* cannot simply be described as AND or XOR since *va* is an abstraction of a set of base activities that may be associated with different ordering structures. Therefore, MIX is used to abstract the complicated ordering structures. A WfMS evaluates *SC* to determine whether *va* can be started. Section 4.5 further discusses *JOIN_ flag*, *SPLIT_ flag*, and the derivation of *SC*. Members of A are called *va*'s *member activities*, and members of D are called *va*'s *member dependencies*. To save space, the abbreviated notation $va = \langle A, D \rangle$ is employed below to represent a virtual activity.

Definition 11 (Virtual dependency). Let $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$ be two distinct virtual activities that are derived from a base process $BP = \langle BA, BD \rangle$. A virtual dependency from va_i to va_j is $vdep(va_i, va_j, R, VC_{ij}) = \{dep(a_x, a_y, R, C_{xy}) | a_x \in A_i, a_y \in A_j,$ and $dep(a_x, a_y, R, C_{xy}) \in BD\}$, where the virtual condition VC_{ij} is a Boolean combination of C_{xy}.

Definition 12 (Virtual loop dependency). Let $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$ be two distinct virtual activities that are derived from a base process $BP = \langle BA, BD \rangle$. A virtual loop dependency from va_i to va_j is $vdep(va_i, va_j, L, VLC_{ij}) = \{dep(a_x, a_y, L, LC_{xy}) | a_x \in A_i, a_y \in A_j,$ and $dep(a_x, a_y, L, LC_{xy}) \in BD\}$, where the virtual loop condition VLC_{ij} equals the loop condition LC_{xy}.

Notably, a loop (and a loop-derived sub-process-view) in the process-view has a corresponding loop (and a loop-derived sub-process) in the base process, as a process-view has a corresponding base process (see the atomicity rule). Therefore, a virtual loop dependency of the process-view only contains one loop dependency of the base process. Section 4.5 further discusses the relationship between $VC(VLC)$ and $C(LC)$ with respect to virtual (loop) dependency. In the following, Theorem 1 proves that the process-view, defined according to Definitions 10–12, preserves original ordering relations. The following lemmas support the proof of Theorem 1. These lemmas are proved in Appendix A.

Lemma 1. *Consider a process-view* $VP = \langle VA, VD \rangle$, *where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 *and* 12, *derived from a base process* $BP = \langle BA, BD \rangle$. *For any two distinct virtual activities* va_i *and* va_j *in VP,* $va_i = \langle A_i, D_i \rangle$ *and* $va_j = \langle A_j, D_j \rangle$: *if there exist a base activity* $a_i \in A_i$ *and a base activity* $a_j \in A_j$ *such that* $a_i > a_j$ *holds in BP, then* $va_i > va_j$ *holds in VP.*

Lemma 2. *Consider a process-view* $VP = \langle VA, VD \rangle$, *where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 *and* 12, *derived from a base process* $BP = \langle BA, BD \rangle$. *Let LP be a loop-derived sub-process of BP; let VLP be a loop-derived sub-process-view of VP; VLP corresponds to LP. For any two distinct*

virtual activities va_i and va_j in VLP, $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$: if there exist a base activity $a_i \in A_i$ and a base activity $a_j \in A_j$ such that $a_i > a_j$ holds in LP, then $va_i > va_j$ holds in VLP.

Lemma 3. *Consider a process-view $VP = \langle VA, VD \rangle$, where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 *and* 12, *derived from a base process $BP = \langle BA, BD \rangle$. For any two distinct virtual activities va_i and va_j in VP, $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$: if $va_i > va_j$ holds in VP, then there exist a base activity $a_i \in A_i$ and a base activity $a_j \in A_j$ such that $a_i > a_j$ holds in BP.*

Lemma 4. *Consider a process-view $VP = \langle VA, VD \rangle$, where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 *and* 12, *derived from a base process $BP = \langle BA, BD \rangle$. Let LP be a loop-derived sub-process of BP; let VLP be a loop-derived sub-process-view of VP; VLP corresponds to LP. For any two distinct virtual activities va_i and va_j in VLP, $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$: if $va_i > va_j$ holds in VLP, then there exist a base activity $a_i \in A_i$ and a base activity $a_j \in A_j$ such that $a_i > a_j$ holds in LP.*

Theorem 1. *Given a process-view $VP = \langle VA, VD \rangle$, as derived from a base process $BP = \langle BA, BD \rangle$, if members of VA follow Definition* 10 *and members of VD follow Definitions* 11 *and* 12, *then VP preserves the ordering relations of BP, and any loop-derived sub-process-view VLP preserves the ordering relations of its corresponding loop-derived sub-process LP.*

Proof. Let va_i and va_j be two different virtual activities in VP, $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$. The following proves that VP preserves the ordering relations of BP; that is, the implied ordering relations between the respective members of va_i and va_j conform to the ordering relations of the base process BP.

Case 1: $va_i > va_j$ *holds in VP*. The proof needs to show that $a_x > a_y$ holds in BP (according to atomicity rule) for all $a_x \in A_i$ and all $a_y \in A_j$. Given that $va_i > va_j$ holds in VP, by Lemma 3, let a_i be the member base activity of va_i and a_j be the member base activity of va_j (i.e., $a_i \in A_i$ and $a_j \in A_j$), and $a_i > a_j$ holds in BP. Since $a_i > a_j$, $a_i \notin A_j$ and $a_j \in A_j$, by Definition 10(1c), $a_i > a_y$ for all $a_y \in A_j$. Furthermore, for any $a_y \in A_j$: since $a_i > a_y$, $a_i \in A_i$ and $a_y \notin A_i$, thus $a_x > a_y$ for all $a_x \in A_i$ (by Definition 10(1c)). Therefore, $a_x > a_y$ holds in BP for all $a_x \in A_i$ and all $a_y \in A_j$.

Case 2: $va_i < va_j$ *holds in VP*. The proof is similar to Case 1 and is omitted.

Case 3: $va_i \infty va_j$ *holds in VP*. The proof needs to show that $a_x \infty a_y$ holds in BP for all $a_x \in A_i$ and all $a_y \in A_j$. Assume that the proposition is false; that is, $a_x \infty a_y$ does not hold in BP for some $a_x \in A_i$ and some $a_y \in A_j$. Let a_i be a member base activity of va_i and a_j be a member base activity of va_j (i.e., $a_i \in A_i$ and $a_j \in A_j$), such that $a_i > a_j$ (or $a_i < a_j$) holds in BP. By Lemma 1, if $a_i > a_j$ holds in BP, then $va_i > va_j$ holds in VP, which contradicts with $va_i \infty va_j$. Similarly, if $a_i < a_j$ holds in BP, then $va_i < va_j$ holds in VP, which also contradicts with $va_i \infty va_j$. Therefore, $a_x \infty a_y$ holds in BP for all $a_x \in A_i$ and all $a_y \in A_j$.

Lemmas 2 and 4 are used to prove that any loop-derived sub-process-view of VP preserves the ordering relations of its corresponding loop-derived sub-process of BP. The proof of this claim is similar to the above proof and is thus omitted. □

4.3. Essential activity

Previous sections have introduced three rules that allow a virtual process to preserve the ordering relations of a base process. However, a process modeler merely wishes to conceal sensitive activities or aggregate detailed activities. In addition to these activities, what activities must be included in order to form a legal virtual activity is not a primary concern, and should be supported by a process-view definition tool. These sensitive or detailed activities are called essential activities.

Definition 13 (Essential activity). Before defining a virtual activity, a modeler must select some activities that are essential to that virtual activity.

The chosen activities are called *essential activities*, and form an essential activity set *EAS*.

Many virtual activities contain the same essential activities and conform to Definition 10. These virtual activities have a "cover" relation with each other, and can be found to share a "minimal virtual activity".

Definition 14 (Cover). Let *EAS* be an essential activity set. A virtual activity $va_i = \langle A_i, D_i \rangle$ is said to *cover* a virtual activity $va_j = \langle A_j, D_j \rangle$ if and only if $A_j \supseteq EAS$, $A_i \supseteq A_j$ and $D_i \supseteq D_j$.

Definition 15 (Minimal virtual activity). For an essential activity set *EAS*, a virtual activity $\langle A, D \rangle$ is called a *minimal virtual activity*, denoted by *min_va*(*EAS*), if it does not cover other virtual activities and $A \supseteq EAS$.

Given an *EAS*, a modeler must identify *min_va*(*EAS*). Besides essential activities, *A* only contains those activities needed to preserve the original ordering relations of the base process, i.e., the *min_va*(*EAS*) only contains essential and adequate information to abstract *EAS*. Adding more activities, which are neither modeler selected nor order preservation needed, into *A* merely adds unnecessary information into *min_va*(*EAS*).

The procedure of defining an order-preserving process-view is summarized as follows: A process modeler must initially select essential activities. The process-view definition tool then automatically generates a legal minimal virtual activity that encapsulates these essential activities. The above two steps are repeated until the modeler determines all required virtual activities. The definition tool then generates all virtual (loop) dependencies between these virtual activities as well as the ordering fields (*JOIN*/*SPLIT*_*flag*) and *SC* of each virtual activity. The process-view definition tool can be implemented using the algorithm proposed in Section 4.5.

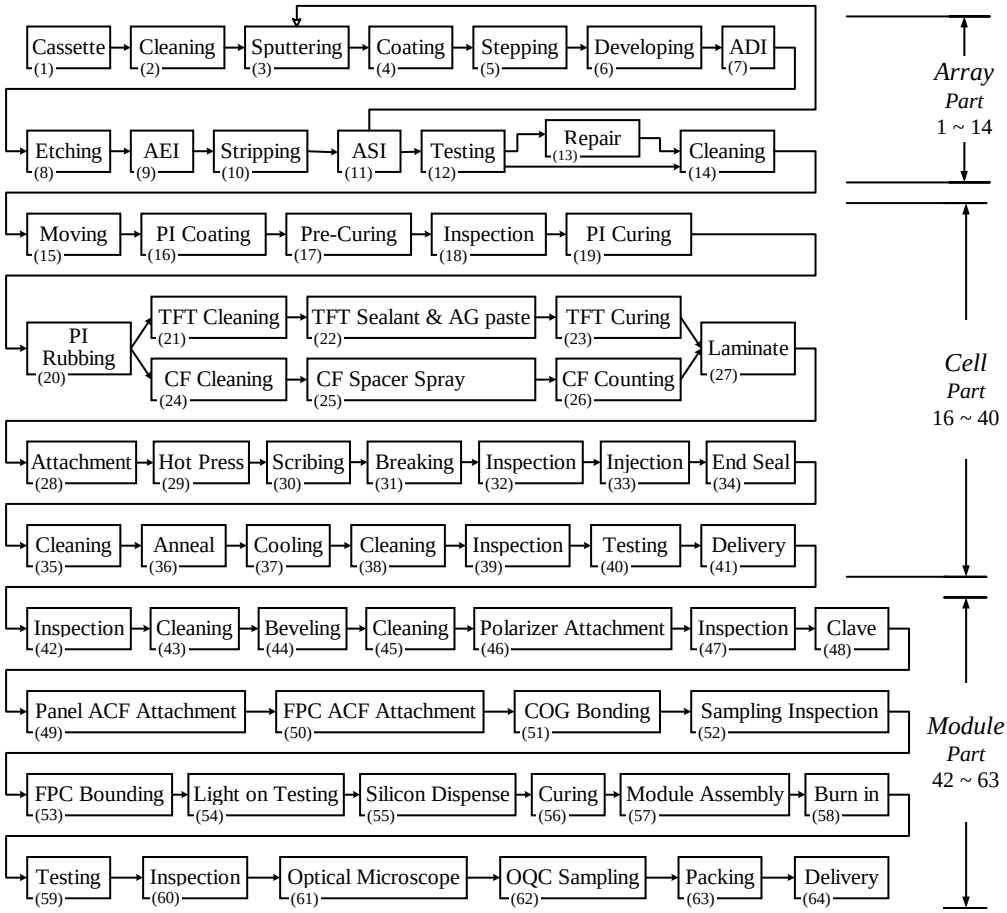
4.4. Illustrative examples

This section uses a manufacturing process as shown in Fig. 11 of a thin film transistor-liquid crystal display (TFT-LCD) company, named HiTEC, to demonstrate the applications of process-view.

The manufacturing process can be divided into three parts: Array, Cell, and Module. Initially, each cassette contains a load of glass substrates. The *Array* part, activities (1)–(14) in Fig. 11, produces TFT panels after repeated sputtering, stepping, developing, and etching on glass substrates. Next, TFT panels move to the Cell part. The *Cell* part, activities (16)–(40), attaches color filters to TFT panels, breaks them into pieces, and injects liquid crystal to produce LC cells. The *Module* part, activities (42)–(63), assembles LC cells, flexible printed circuits, chips, and casing to produce LCD modules. Finally, these LCD modules are delivered to downstream customers such as notebook computer and monitor manufacturers. Delivery activities, (41) and (64), are outsourced to a transport company.

HiTEC has three fabrication factories: FAB I, II, and III. FAB I and II produce Array and Cell Parts, while FAB III handles Module parts. According to the demands of different roles, a process modeler can design an appropriate view for a role without being restricted by the original process definitions. The following discussion provides two examples of the roles: a factory director and a marketer.

First, the application of the proposed methodology to defining a process-view is demonstrated. The factory director of FAB II must know the aggregated information and more about the *Array* and *Cell* processes. A process modeler can easily use the order-preserving approach to define a process-view for the director. For example, when the modeler wants to use a virtual activity to abstract activities (16), (19), (20), (22), and (25), the process-view definition can automatically derive a legal virtual activity. Fig. 12 displays the prototype system when generating a *min_va*(*EAS*), where $EAS = \{16, 19, 20, 22, 25\}$. The tool automatically generates a *min_va*(*EAS*) based on the chosen *EAS*. Following the determination of all virtual activities, i.e., each base activity is contained by a virtual activity, the tool automatically generates a process-view, as shown in Fig. 13 where each virtual activity is annotated with its



ACF : An-isotropic Conductive Film
ADI: After Developing Inspection
AG: Anti-Glare
ASI: After Stripping Inspection
CF: Color Filter
COG: Chip on Glass
FPC : Flexible Printed Circuit
LC: Liquid Crystal
OQC: Outgoing Quality Control
PI: Polyimide
TFT: Thin Film Transistor

Fig. 11. The manufacturing process of a TFT-LCD factory.

member activity(s) in the braces. The process-view ensures the preservation of the original ordering relations.

Marketers must monitor the progress of the manufacturing process to improve their provision of customer service. The process-view shown in Fig. 14 informs marketers of the status of order fulfillment in the manufacturing department, for example, the Cell activity represents the progress of activities (16)–(40) in Fig. 11. Another scenario is HiTEC authorizing its customers to access process-views. Customers can actively monitor the progress of order processing through their process-views. A process modeler can use diverse customer requirements as a basis for designing various customized process-views to provide personalized service.

4.5. Algorithm

This section introduces algorithms to derive an order-preserving process-view. The algorithm first derives the member activities and dependencies of a minimal virtual activity based on the essential

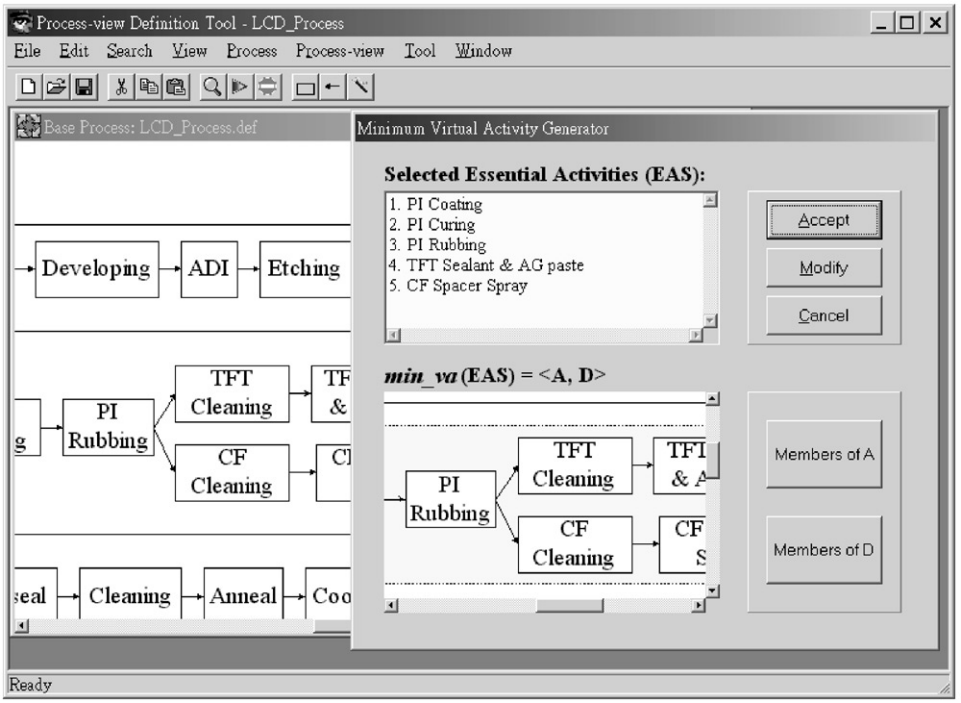


Fig. 12. Generating a *min_va*(*EAS*) using the process-view definition tool.

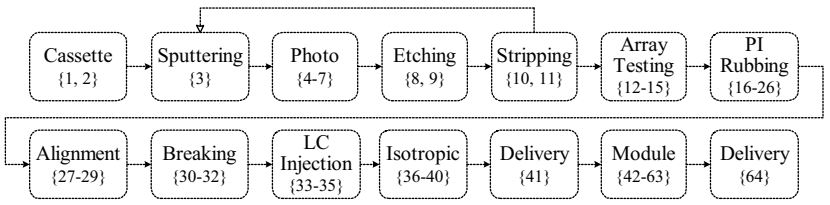


Fig. 13. A process-view for the factory director of FAB II.

Fig. 14. A process-view for marketers.

activities specified by a modeler. Subsequently, how to derive virtual dependencies and the *JOIN_flag*, *SPLIT_flag*, and *SC* field of each virtual activity in the process-view is discussed.

4.5.1. Minimal virtual activity generator

For a given essential activity set *EAS*, Fig. 15 shows the algorithm capable of obtaining an $min\_va(EAS) = \langle A, D \rangle$. Because *D* can be derived from *A* and *EAS* is known, the members of *A* must be identified. Let *BP′* be the base process *BP* or any loop-derived sub-process of *BP*. According to the definition of a virtual activity (Definition 10(1c)), a legal virtual activity *A* must satisfy the order-preserving condition: the ordering relations between *x* and all members of *A* that belong to *BP′* are identical for any base activity $x \in BA'$ and $x \notin A$.

As mentioned in Section 4.3, an activity *x*, $x \notin EAS$, is included in *A* for order preservation. *EAS* is obviously a starting point for identifying *x*. The algorithm begins from *EAS*, by initializing an activity set *TAS* that equals *EAS*, to check whether *TAS* is a legal (i.e., order-preserving) virtual

```
(1)  procedure VAGenerator (base process BP = ⟨BA, BD⟩, essential activity set EAS)
(2)  begin
(3)    temp activity set TAS = EAS
(4)    repeat
(5)      an activity set TAS1 = TAS
(6)      adjacent activity set AAS = { x | x, y ∈ BA, x ∉ TAS, y ∈ TAS and dep(x, y, _, _) ∈ BD }
(7)      a process set PS = { p | p is BP or a loop-derived sub-process of BP}
(8)      while AAS is not empty do
(9)        select an activity x from AAS
(10)       remove x from AAS
(11)       if ∃y, z ∈ TAS, ∃BP′ = ⟨BA′, BD′⟩ ∈ PS, and x, y, z ∈ BA′
                such that (( x > y holds in BP′ but x > z does not holds in BP′ ) or
                           ( x < y holds in BP′ but x < z does not holds in BP′ ) or
                           ( x ∞ y holds in BP′ but x ∞ z does not holds in BP′ ) )
(12)       /* The ordering relations between x and all base activities of TAS that belong to BP′
              are not identical */
(13)       then add x to TAS
(14)       end if
(15)     end while
(16)   until TAS == TAS1
(17)   an activity set A = TAS
(18)   a dependency set D = { dep(x, y, _, _) | x, y ∈ A, and dep(x, y, _, _) ∈ BD }
(19)   min_va(EAS) = ⟨A, D⟩
(20) end
```

Fig. 15. The algorithm of a minimal virtual activity generator.

activity. If TAS is not legal, TAS is updated by including activities that violate the order-preserving condition. To determine which of the activities should be added into TAS to form a legal and minimal virtual activity, the algorithm considers the activities that are adjacent to members of TAS. The algorithm determines whether adjacent activities of TAS satisfy the order-preserving condition (line 11). TAS is updated during the *while* loop (lines 8–15), by adding adjacent activities that violate the order-preserving condition. If TAS is updated, the *repeat-until* loop is repeated to check the order-preserving condition. The *repeat-until* loop (lines 4–16) continues to repeat until no more adjacent activity is added into TAS (line 16, $TAS == TAS_1$), i.e., all adjacent activities of TAS satisfy the order-preserving condition. Finally, TAS is a legal virtual activity and A is set to equal TAS.

Following the determination of A, the members of D are those dependencies whose succeeding and preceding activity are both members of A (Definition 10(2)). The minimal virtual activity of EAS, $min\_va(EAS)$, equals $\langle A, D \rangle$.

Since this virtual activity conforms to Definition 10, it is a legal virtual activity. Moreover, the algorithm checks the ordering relations from adjacent activities, creating a minimal virtual activity. The proof is shown in Theorem 2.

Theorem 2. *Given a base process BP and an essential activity set EAS, the virtual activity va, as generated by the algorithm VAGenerator, is a legal (order-preserving) virtual activity, and also a minimal virtual activity of EAS.*

Proof. The procedure determines whether adjacent activities of TAS satisfy the order-preserving condition. TAS is updated during the *while* loop (lines 8–15), by adding adjacent activities that violate the order-preserving condition. TAS is repeatedly updated until no more adjacent activity is added to TAS (line 16, $TAS == TAS_1$); that is, all adjacent activities of A (i.e., AAS) satisfy the order-preserving condition. The following proves that all activities, other than adjacent activities of A, also satisfy the order-preserving condition. Assume that an activity x exists, where $x \notin A$ and

x is not adjacent to any members of A, such that x violates the order-preserving condition. Let y_1 and y_2 be the member activities of A that cause the violation of the condition.

Case 1: $x > y_1$ *holds in BP, but* $x > y_2$ *does not hold in BP*. Given that $x > y_1$ and x is not adjacent to any activity in A, there must exist a path from x to z and a path from z to y_1, where z is an adjacent activity of A. Thus, $x > z$ and $z > y_1$ hold in BP. $z > y_1$ implies that $z > y_2$ also holds in BP since z satisfies the order-preserving condition. It further implies that $x > y_1$ and $x > y_2$ hold in BP, which contradicts the assumption that $x > y_1$ holds but $x > y_2$ does not hold in BP.

Case 2: $x < y_1$ *holds in BP, but* $x < y_2$ *does not hold in BP*. The proof is similar to Case 1 and is omitted.

Case 3: $x \infty y_1$ *holds in BP, but* $x \infty y_2$ *does not hold in BP*. Given that $x \infty y_2$ does not hold in BP, assume that $x > y_2$ holds in BP. There exist a path from x to z and a path from z to y_2, where z is an adjacent activity of A, since $x > y_2$ and x is not adjacent to any activity in A. Thus, $x > z$ and $z > y_2$ hold in BP. $z > y_2$ implies that $z > y_1$ also holds in BP, since z satisfies the order-preserving condition. It further implies that $x > y_1$ and $x > y_2$ hold in BP, which contradicts the assumption.

The proof of the preservation of the ordering relations held in the loop-derived sub-processes of BP is similar to the above proof and is omitted.

Thus, the generated virtual activity $va = \langle A, D \rangle$ conforms to Definition 10.

Next, the following proves that va is a minimal virtual activity of EAS. Assume that va is not minimal, then a legal and minimal virtual activity $mva = \langle A_m, D_m \rangle$ exists such that $A \supset A_m$. The procedure begins from EAS, by initializing TAS to be EAS, to check the ordering relations of the adjacent activities. TAS is updated during the *while* loop (lines 8–15), by adding adjacent activities that violate the order-preserving condition. Assume that a TAS is formed during the *while* loop of the procedure, where $TAS \subset A_m$. Additionally, an adjacent activity x of TAS, $x \notin A_m$, can be found such that x violates the order-preserving condition. Notably, an adjacent activity is added into TAS according to the *if-condition* (line 11). If the adjacent activity belongs to A_m, then the process proceeds until an adjacent activity that does not belong to A_m can be found; otherwise, the procedure generates A_m. Since the ordering relations between x and the members of TAS violate the order-preserving condition, there exist two activities y_1 and y_2 in TAS, such that the ordering relation between x and y_1 differs from the ordering relation between x and y_2 (the ordering relation means the ordering relation held in BP or a loop-derived sub-process of BP). Moreover, y_1 and y_2 belong to A_m since $TAS \subset A_m$. Thus, the ordering relations between x and members of A_m also violate the order-preserving condition. Consequently, *mva* is not a legal virtual activity, which contradicts the assumption. Therefore, *va* is a minimal virtual activity. □

Example 1. This example illustrates the steps required to generate *min_va*(EAS), where $EAS = \{a_{16}, a_{19}, a_{20}, a_{22}, a_{25}\}$ and the base process BP is the LCD manufacturing process described in Section 4.4. Part of the LCD process shown in Fig. 11 is redrawn in Fig. 16(a). The algorithm creates a copy of EAS, i.e., TAS, as an initial set (see line 3 in Fig. 15). The *repeat-until* loop uses TAS as a seed to identify the member activities of *min_va*(EAS) (see lines 4–16).

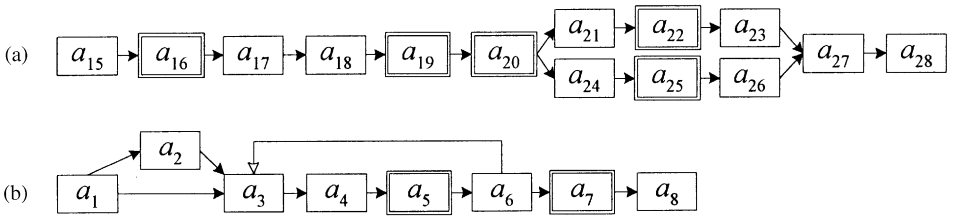


Fig. 16. Two process examples.

Initially, $AAS = \{a_{15}, a_{17}, a_{18}, a_{21}, a_{23}, a_{24}, a_{26}\}$ (see line 6). This example only need to consider the ordering relations of BP since it does not contain loops (see line 7). The subsequent *while* loop verifies whether the adjacent activities satisfy the order-preserving condition (see lines 8–15). For example, activity a_{23} is added into TAS since $a_{23} < a_{22}$ but $a_{23} \infty a_{25}$. However, activity a_{15} is not added into TAS since the ordering relations between a_{15} and all members of TAS are "$>$". After checking all members of AAS, activities $a_{17}, a_{18}, a_{21}, a_{24}, a_{23}$, and a_{26} are added into TAS.

Since TAS is updated ($TAS \neq TAS_1$), i.e., TAS does not follow the definition of virtual activity, the *repeat-until* loop repeats using the revised TAS, $\{a_{16}, a_{17}, a_{18}, a_{19}, a_{20}, a_{21}, a_{22}, a_{23}, a_{24}, a_{25}, a_{26}\}$ (see line 16). During the next iteration, $AAS = \{a_{15}, a_{27}\}$. TAS remains unchanged during the *while* loop since the members of AAS satisfy the order-preserving condition. Under the circumstances, the ordering relations between x and all members of TAS are identical in BP for any $x \in BA$ and $x \notin TAS$, i.e., TAS follows the definition of a virtual activity, and the *repeat-until* loop stops.

For the $min\_va(EAS) = \langle A, D \rangle$, A equals TAS and the dependency set D contains the following dependencies: $dep(a_{16}, a_{17}, R, \_)$, $dep(a_{17}, a_{18}, R, \_)$, $dep(a_{18}, a_{19}, R, \_)$, $dep(a_{19}, a_{20}, R, \_)$, $dep(a_{20}, a_{21}, R, \_)$, $dep(a_{20}, a_{24}, R, \_)$, $dep(a_{21}, a_{22}, R, \_)$, $dep(a_{22}, a_{23}, R, \_)$, $dep(a_{24}, a_{25}, R, \_)$, and $dep(a_{25}, a_{26}, R, \_)$ (see lines 18–19).

Example 2. This example illustrates how to derive the $min\_va(EAS)$ for the base process BP as shown in Fig. 16(b) and $EAS = \{a_5, a_7\}$. Initially, $AAS = \{a_4, a_6, a_8\}$, $TAS = \{a_5, a_7\}$, and $PS = \{BP, LP(a_3, a_6)\}$. a_6 is added into TAS because $a_5 > a_6$ holds in BP but $a_7 > a_6$ does not hold in BP. a_8 is not added to TAS because $a_7 > a_8$ and $a_6 > a_8$ hold in BP. Notably, a_4 is added into TAS because $a_4 < a_5$ (derived from the path a_5, a_6, a_3, a_4) holds in BP but $a_4 < a_7$ does not hold in BP. Therefore, TAS changes to $\{a_4, a_5, a_6, a_7\}$ and *repeat-until* loop repeats. During the second iteration, $AAS = \{a_3, a_8\}$. a_8 is not added into TAS because $a_4 > a_8$, $a_5 > a_8$, $a_6 > a_8$, and $a_7 > a_8$ hold in BP. However, a_3 is added into TAS because $a_3 < a_6$ (derived from the path a_6, a_3) holds in BP but $a_3 < a_7$ does not hold in BP. Therefore, TAS is updated to $\{a_3, a_4, a_5, a_6, a_7\}$ and the *repeat-until* loop repeats again. During the third iteration, $AAS = \{a_1, a_2, a_8\}$. TAS remains unchanged during the *while* loop since the ordering relations between each adjacent activity and the members of TAS are identical in BP and $LP(a_3, a_6)$. Consequently, the *repeat-until* loop stops and $A = \{a_3, a_4, a_5, a_6, a_7\}$, $D = \{dep(a_3, a_4, R, \_)$, $dep(a_4, a_5, R, \_)$, $dep(a_5, a_6, R, \_)$, $dep(a_6, a_7, R, \_)$, $dep(a_6, a_3, L, \_)\}$.

Example 3. Given a base process BP as shown in Fig. 16(b) and $EAS = \{a_4, a_6\}$, the generation of the $min\_va(EAS)$ is explained below. Initially, $AAS = \{a_3, a_5, a_7\}$, $TAS = \{a_4, a_6\}$, and $PS = \{BP, LP(a_3, a_6)\}$. According to the ordering relations of BP, TAS is unchanged (for a_3: $a_3 > a_4$, $a_3 > a_6$, $a_3 < a_4$, $a_3 < a_6$; for a_5: $a_5 > a_4$, $a_5 > a_6$, $a_5 < a_4$, $a_5 < a_6$; for a_7: $a_7 < a_4$, $a_7 < a_6$). However, according to the ordering relations of $LP(a_3, a_6)$, a_5 is added into TAS (for a_3: $a_3 > a_4$, $a_3 > a_6$; for a_5: $a_5 < a_4$, $a_5 > a_6$). Therefore, TAS is updated to $\{a_4, a_5, a_6\}$ and the *repeat-until* loop repeats. During the second iteration, $AAS = \{a_3, a_7\}$. TAS remains unchanged during the *while* loop since the ordering relations of BP and $LP(a_3, a_6)$ are preserved. Hence, for the $min\_va(EAS)$, $A = \{a_4, a_5, a_6\}$ and $D = \{dep(a_4, a_5, R, \_)$, $dep(a_5, a_6, R, \_)\}$.

4.5.2. Virtual dependency and virtual loop dependency

Following the generation of all virtual activities, the process-view definition tool derives virtual dependencies by Definition 11. First, the members of a virtual dependency must be determined, after which the VC field of each virtual dependency must be derived.

Given the virtual activity set VA of a process-view VP derived from a base process BP, whether or not a virtual dependency is associated with two virtual activities can be determined. For any two distinct virtual activities $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$: if $\exists\ a_x \in A_i$ and $\exists\ a_y \in A_j$ such that $dep(a_x, a_y, R, C_{xy})$ exists in BP, then $vdep(va_i,$

va_j, R, VC_{ij}) exists in VP and $dep(a_x, a_y, R, C_{xy})$ is a member of $vdep(va_i, va_j, R, VC_{ij})$. After checking each base dependency, all virtual dependencies and their members can be derived.

The following illustrates the derivation of VC field of a virtual dependency. The *JOIN_ flag* of a base activity determines how the conditions of incoming dependencies are combined to derive starting condition of the base activity. Therefore, for the members of a virtual dependency, the conditions of base dependencies that share the same succeeding base activity are combined using the *JOIN_flag* of that succeeding base activity. According to the atomicity rule, a virtual activity is started if one member activity is started. Therefore, the conditions derived from different succeeding base activities are then combined using Boolean OR. Restated, given two virtual activities $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$, where $A_j = \{a_{y1}, a_{y2}, \ldots, a_{yn}\}$, for each a_{yk}, $k = 1, 2, \ldots, n$: Let (1) $C_{m,yk}$ represent the condition of a dependency from a member of A_i to a_{yk}, for $m = 1, 2, \ldots, l_k$; (2) f_k be the *JOIN_ flag* of a_{yk}; (3) C_{yk} represent the joined condition of all dependencies from members of A_i to a_{yk}, i.e., $C_{yk} = (C_{1,yk} f_k C_{2,yk} \ldots f_k C_{l_k,yk})$. For the virtual dependency $vdep(va_i, va_j, R, VC_{ij})$, $VC_{ij} = (C_{y1}$ OR $C_{y2} \ldots$ OR $C_{yn})$.

In Fig. 17(a), for example, $VC_{12} = (C_1$ OR $C_2)$, i.e., if C_1 or C_2 is true, then VC_{12} is true. However, in Fig. 17(b), C_1 and C_2 are combined using the *JOIN_ flag* of a_2, i.e., $VC_{12} = (C_1$ AND/XOR $C_2)$. For the complex combination shown in Fig. 17(c), $VC_{12} = ((C_1$ AND/XOR $C_3)$ OR $(C_2$ AND/XOR $C_4))$. In Fig. 17(d), $VC_1 = (C_1$ AND/XOR $C_3)$, $VC_2 = (C_2$ AND/XOR $C_4)$, $VC_3 = C_5$.

Deriving virtual loop dependencies is similar to the derivation of virtual dependency. Given the virtual activity set VA of a process-view VP derived from BP, for any two distinct virtual activities $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$: if $\exists$ $a_x \in A_i$ and $\exists$ $a_y \in A_j$ such that $dep(a_x, a_y, L, LC_{xy})$ exists in BP, then $vdep(va_i, va_j, L, VLC_{ij})$ exists in VP. According to Definition 12, $VLC_{ij} = LC_{xy}$.

4.5.3. Ordering structure and starting condition

Following the generation of all virtual dependencies, the ordering fields (*JOIN/SPLIT_flag*) and starting conditions of each virtual activity can be derived. If a virtual activity has a single outgoing virtual dependency, its *SPLIT_flag* is NULL. Otherwise, when multiple outgoing virtual dependencies exist, the *SPLIT_ flag* of the virtual activity is MIX. The *SPLIT_ flag* of the virtual activity cannot simply be AND or XOR, since a virtual activity abstracts a set of base activities that may be concurrently associated with AND-SPLIT and XOR-SPLIT.

Similarly, if a virtual activity has a single incoming virtual dependency, its *JOIN_flag* is NULL, while if it has multiple incoming virtual dependencies, its *JOIN_ flag* is MIX. For a base activity, the *JOIN_ flag* determines the relationship between its starting condition (SC) and the conditions (C) of its incoming base dependencies.

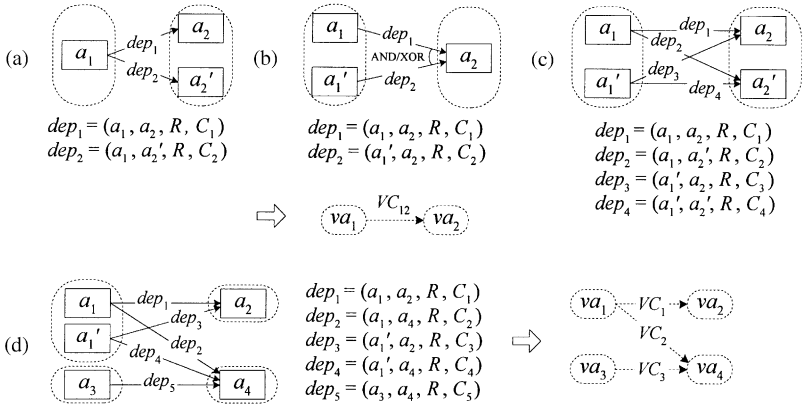


Fig. 17. Four examples of virtual dependencies.

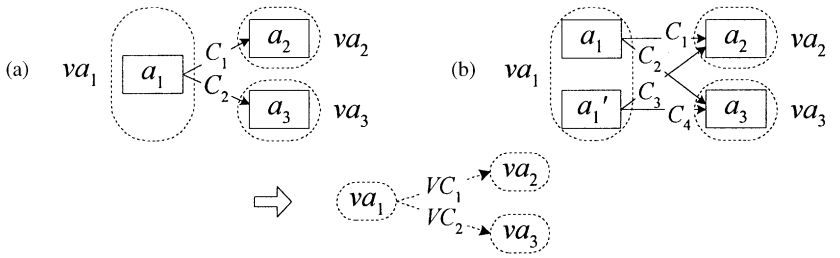


Fig. 18. Two examples of the split structure in a process-view.

Nevertheless, for a virtual activity, MIX-JOIN abstracts the existence of different join structures in its member base activities. Therefore, the starting condition (SC) of a virtual activity cannot simply use the *JOIN_flag* to combine the conditions (VC) of incoming virtual dependencies. MIX-SPLIT/JOIN is used to represent multiple path structures, and the starting of a virtual activity depends on the SC field, which is derived as follows.

A virtual activity va is started if one of its member activities is started (atomicity rule). Therefore, the starting condition of each member activity of va must be determined, after which the SC of va equals the Boolean OR combination of the starting condition of each member activity. If $va = \langle A, D \rangle$, $A = \{a_1, a_2, \ldots, a_n\}$, and the starting condition of a_i is $SC(a_i)$ for $i = 1 \ldots n$, then the starting condition of va is $SC(va) = (SC(a_1)\ \text{OR}\ SC(a_2) \ldots \text{OR}\ SC(a_n))$. Consequently, $SC(va)$ is true if the starting condition of one member activity is satisfied.

In Fig. 18(a), for example, $VC_1 = C_1$ and $VC_2 = C_2$, $SC(a_2) = C_1$ and $SC(a_3) = C_2$, $SC(va_2) = SC(a_2)$ and $SC(va_3) = SC(a_3)$. Moreover, in Fig. 18(b), $VC_1 = (C_1\ \text{AND/XOR}\ C_3)$ and $VC_2 = (C_2\ \text{AND/XOR}\ C_4)$. Whether a_2 can be started depends on its *JOIN_flag* (AND/XOR), i.e., $SC(a_2) = (C_1\ \text{AND/XOR}\ C_3)$. $SC(va_2) = SC(a_2)$. $SC(a_3) = (C_2\ \text{AND/XOR}\ C_4)$. $SC(va_3) = SC(a_3)$. In Fig. 19, if the *JOIN_flag* of a_4 is AND and the *JOIN_flag* of a_4' is XOR, then $VC_1 = (C_1\ \text{OR}\ C_2)$ and $VC_2 = (C_3\ \text{OR}\ C_4)$. $SC(a_4) = (C_1\ \text{AND}\ C_3)$ and $SC(a_4') = (C_2\ \text{XOR}\ C_4)$. $SC(va_4) = (SC(a_4)\ \text{OR}\ SC(a_4')) = ((C_1\ \text{AND}\ C_3)\ OR\ (C_2\ \text{XOR}\ C_4))$. Under such circumstances, the *JOIN_flag* of va_4 cannot merely be AND or XOR. MIX is used to abstract such combinations and a WfMS evaluates SC to trigger va_4.

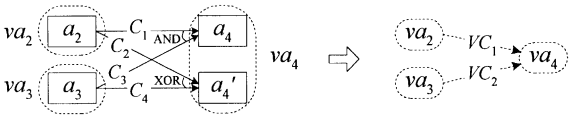


Fig. 19. Example of the join structure in a process-view.

4.5.4. Prototype system

A prototype system is currently being implemented based on the above discussion. As displayed in Fig. 12, the tool can automatically generate a legal and minimal virtual activity based on the essential activities chosen by a process modeler. Once all base activities have been contained by virtual activities, the tool automatically generates an order-preserving process-view based on the defined virtual activities. Currently, a modeler must use the prototype system to define a base process. In the future, the prototype will be enhanced to interpret base processes that are defined by using commercial products.

5. Related work

Workflow models, in which business processes are formally described to generate process definitions, are generally classified as communication-based and activity-based [1]. The former attempts to identify process objectives, while the latter focuses on identifying process structures. A survey [1] of commercial WfMSs revealed that most supported workflow models are activity-based.

The activity-based approach is easily understandable when modeling business tasks and their ordering relations. Owing to the top-down decomposition of a process, activity-based methods yield different hierarchical abstractions. However, as mentioned in Section 1, these hierarchical abstractions cannot provide each organizational level and unit with an appropriate view of a process. This work contributes to introducing the notion of view into WfMSs, and proposing a systematic procedure to derive adequate process abstractions from a base process for different participants.

This work enhances the capability of process abstraction in conventional activity-based process models, while the enhancement of the activity-based approach has also attracted considerable interest. Since process modeling can be considered from various aspects, such as functional and information aspects [16,17], numerous investigations have enhanced the activity-based approach by combining it with other aspects. These investigations have focused on specifying the interrelationships among these aspects. For example, Gruhn [18] proposed a model to integrate the modeling of activity, data, and organization. ARIS [19] describes business processes from the aspects of function, organization, data, output, and control. Moreover, some studies have exploited object-oriented technology or Petri nets to combine the modeling of control and data flow [20–23]. Such enhancements concern the integration of multiple aspects in a workflow model. However, this work focuses on deriving abstracted processes for different organizational roles. Notably, the term "view" used in some of above works represents an aspect of process modeling, while herein it represents a process abstraction.

Several formal process modeling techniques include the notion of process abstraction, such as process algebras and Petri-Nets [8–11]. These models can define some activities as *silent* activities (also called τ activities) that are not observable. By renaming activities to silent activities, the desired abstraction can be obtained. In contrast, process-views are derived through the bottom-up aggregation of activities to provide various levels of abstraction of a process. Conventional abstraction may be considered as *partial abstraction* since it provides partial observability of a process. Relative to partial abstraction, the proposed approach is considered to be *aggregate abstraction*, since it provides adaptable granularity of a process via bottom-up aggregation, i.e., a virtual activity may represent an aggregation of a set of base activities.

Partial abstraction does not reveal the progress status of the silent activities of a base process. For example, if a view "$a_1 \rightarrow a_3 \rightarrow a_5 \rightarrow a_8$" is partially abstracted from the process shown in Fig. 16(b), then the view does not expose the progress of silent activities (i.e., a_2, a_4, a_6, and a_7). However, if the proposed approach defines a process-view as "$\{a_1, a_2\} \rightarrow \{a_3\} \rightarrow \{a_4, a_5, a_6\} \rightarrow \{a_7, a_8\}$", the progress of the virtual activity which contains a_1 and a_2 expresses the aggregated progress of these two base activities. In addition to concealing sensitive details that partial abstraction can provide, process-views also provide high-level managers with aggregated information on a desired process. Furthermore, a process-view can be systematically derived from a base process. Nevertheless, partial abstraction may assist a process modeler in identifying essential activities needed to define a process-view.

Aggregate abstraction generally includes partial abstraction. For example, given a virtual activity va_1 which is an aggregation of base activities a_1, a_2, and a_3, if the weight of a_1 and a_3 are zero and the weight of a_2 is one, then va_1 can be viewed as a partial abstraction of a_1, a_2, and a_3. The binary weight implies the notion of visible/invisible or important/unimportant that is the core of partial abstraction. Thus, partial abstraction can be derived from aggregate abstraction by using the concept of weight.

Various activity-based process models have been suggested for workflow management, such as the WfMC process model [7] and the Petri-Net variants [24,25]. Although not formally specifying the operational semantics of process definitions as Petri-Net-based workflow models [25], the WfMC process model has been extensively used to design and implement WfMSs. Besides, much workflow-related research is based on the WfMC process model. Accordingly, this work revises the WfMC process model to design the process-view model. Consequently, the process-view model can be

further extended to be incorporated into commercial products, since WfMC standards are accepted by major workflow vendors. This work focuses on enhancing the WfMC process model to derive process-views, i.e., aggregate process abstractions. Deriving the aggregate process abstractions for other activity-based models such as the Petri-Net variants is worth exploring. However, such a study is beyond the scope of this work and is proposed as a topic of future work.

Van der Aalst [26] proposed a novel generic workflow model to provide a manager with an aggregated view of variants for the same workflow process. Dynamic change has created multiple variants of the same process. A representative process, in which each activity represents the aggregation of all identical activities of these process variants, is used as the aggregated view. The generic process model focuses on providing aggregated information of dynamically changing process variants, while the process-view proposed herein aggregates different activities within a process to create various abstracted views.

Effective management of collaborative processes in virtual enterprises is important [27,28]. Related interorganizational workflow models, e.g., [29,30], achieved information concealment (autonomy) but were unable to monitor the progress of other cooperating organizations. Georgakopoulos et al. [3] used a service activity to abstract an entire process of a service provider. A service activity implements a service interface that defines several application-specific states and operations. Application-specific activity states extend the generic activity states defined by WfMC [31] to express possible process states. A service consumer is only aware of the state transition diagram of a service activity (information concealment), and can use the operations and states defined by the service interface to monitor the progress of a service provider's process (progress monitoring). In the proposed approach, a modeler can define various process-views to achieve different levels of information concealment. Furthermore, the progress of base processes can be monitored through virtual activities and virtual processes. Notably, this work focuses on illustrating the process-view model and the novel approach to derive a process-view. This work on process-view will be further extended in the future to support information concealment and progress monitoring of collaborative processes in virtual enterprises.

6. Conclusion and future work

This work proposes a novel concept of process abstraction: process-view. Process-view enhances the conventional activity-based model to satisfy the diverse needs for obtaining abstracted process information. A process modeler can easily use a process-view definition tool to provide numerous views of a business process for different levels, divisions, and enterprises. The process-view achieves information abstraction and progress monitoring. Each role can obtain adequate information on a business process by setting up a role-related process-view, thereby facilitating hierarchical coordination within an organizational unit and horizontal coordination across multiple organizations (internal or external). The proposed approach increases the flexibility and functionality of current WfMSs.

Moreover, given the importance of execution order in business processes, this work also proposes an order-preserving approach to construct a process-view that preserves the original execution order of its base process. The proposed algorithm automatically derives minimal virtual activities and related virtual dependencies to generate an order-preserving process-view. The algorithm assists vendors in implementing process-view definition tools in their commercial systems. A real world example is used to demonstrate the feasibility of applying process-views.

According to the atomicity rule, the execution state of a virtual activity is either started or completed. However, a base activity may have more semantic states such as suspended or aborted (i.e., abnormal completion) state. Determining the state of a virtual activity is difficult, for example, if the current states of its three member activities are suspended, started, and aborted. This problem becomes more complicated when a process modeler is allowed to define more application-specific

activity states, such as CMI approach [3]. To express the progress information of process-views semantically, the issue of state abstraction requires further investigations.

This work currently defines the produced/consumed data of a virtual activity as a set of the produced/consumed data of member activities. However, according to the demands of different roles, a process modeler may wish to define process-view relevant data as an aggregation of base process relevant data (e.g., summation or average), or a selected portion of base process relevant data. Furthermore, process relevant data may have various semantic meanings and definitions. For example, a sales order or an insurance contract have various semantics in different steps of their processing workflow. Abstracting process relevant data from these aspects is a difficult problem, and future enhancement should provide more advanced abstraction of process-view data.

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Appendix A. Proof of lemma

Lemma 1. *Consider a process-view* $VP = \langle VA, VD \rangle$, *where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 *and* 12, *derived from a base process* $BP = \langle BA, BD \rangle$. *For any two distinct virtual activities* va_i *and* va_j *in* VP, $va_i = \langle A_i, D_i \rangle$ *and* $va_j = \langle A_j, D_j \rangle$: *if there exist a base activity* $a_i \in A_i$ *and a base activity* $a_j \in A_j$ *such that* $a_i > a_j$ *holds in BP, then* $va_i > va_j$ *holds in VP.*

Proof. Let va_i and va_j be two distinct virtual activities in VP, $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$, where va_i contains a base activity a_i and va_j contains a base activity a_j (i.e., $a_i \in A_i$, $a_j \in A_j$), and $a_i > a_j$ holds in BP. A path p from a_i to a_j must exist, since $a_i > a_j$ holds in BP. The following proves this lemma by induction on the length of path p from a_i to a_j.

When the length of the path p from a_i to a_j is one, $dep(a_i, a_j, \_, \_)$ exists in BP. According to Definitions 11 and 12, $vdep(va_i, va_j, \_, \_)$ exists in VP, and thus $va_i > va_j$ holds in VP.

The induction hypothesis assumes that for any two distinct virtual activities va_r and va_s in VP, $va_r = \langle A_r, D_r \rangle$ and $va_s = \langle A_s, D_s \rangle : va_r > va_s$ holds in VP if there exist a base activity $a_r \in A_r$, a base activity $a_s \in A_s$, and a path from a_r to a_s with length $\leqslant k$ such that $a_r > a_s$ holds in BP.

The induction step must show that $va_i > va_j$ holds in VP, when the length of the path p from a_i to $a_j \leqslant k + 1$. Let a_h be a base activity on the path p from a_i to a_j, where $a_h \neq a_i$ and a_j. The length of the subpath of p from a_i to $a_h \leqslant k$ since the length of $p \leqslant k + 1$. Besides, the length of the subpath of p from a_h to $a_j \leqslant k$. Moreover, $a_i > a_h$ holds in BP and $a_h > a_j$ holds in BP. If $a_h \in A_i$ or $a_h \in A_j$, then $va_i > va_j$ holds in VP. On the other hand, if a_h is a member of va_h, where $va_h \in VA$, $va_h \neq va_i$ and va_j, then $va_i > va_h$ holds in VP according to the induction hypothesis, since $a_i > a_h$ holds in BP and the length of the path from a_i to $a_h \leqslant k$. Similarly, $va_h > va_j$ holds in VP. Consequently, $va_i > va_j$ holds in VP, since both $va_i > va_h$ and $va_h > va_j$ hold in VP. □

Lemma 2. *Consider a process-view* $VP = \langle VA, VD \rangle$, *where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 and 12, *derived from a base process* $BP = \langle BA, BD \rangle$. *Let LP be a loop-derived sub-process of BP*; *let VLP be a loop-derived sub-process-view of VP*; *VLP corresponds to LP. For any two distinct virtual activities* va_i *and* va_j *in VLP,* $va_i = \langle A_i, D_i \rangle$ *and* $va_j = \langle A_j, D_j \rangle$: *if there exist a base activity* $a_i \in A_i$ *and a base activity* $a_j \in A_j$ *such that* $a_i > a_j$ *holds in LP, then* $va_i > va_j$ *holds in VLP.*

Proof. The proof is similar to the proof of Lemma 1 and is omitted. □

Lemma 3. *Consider a process-view* $VP = \langle VA, VD \rangle$, *where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 and 12, *derived from a base process* $BP = \langle BA, BD \rangle$. *For any two distinct virtual activities* va_i *and* va_j *in VP*, $va_i = \langle A_i, D_i \rangle$ *and* $va_j = \langle A_j, D_j \rangle$: *if* $va_i > va_j$ *holds in VP, then there exist a base activity* $a_i \in A_i$ *and a base activity* $a_j \in A_j$ *such that* $a_i > a_j$ *holds in BP.*

Proof. Let va_i and va_j be two distinct virtual activities in VP, $va_i = \langle A_i, D_i \rangle$ and $va_j = \langle A_j, D_j \rangle$, where $va_i > va_j$ holds in VP. A path vp from va_i to va_j must exist, since $va_i > va_j$ holds in VP. The following proves this lemma by induction on the length of the path vp from va_i to va_j .

When the length of the path vp is one, $vdep(va_p, va_q, \_, \_)$ exists in VP. By Definitions 11 and 12, $dep(a_i, a_j, \_, \_)$ exists in BP, where base activities a_i and a_j are members of va_i and va_j, respectively, (i.e., $a_i \in A_i$ and $a_j \in A_j$). Thus, $a_i > a_j$ holds in BP.

The induction hypothesis assumes that for any two distinct virtual activities va_r and va_s in VP, $va_r = \langle A_r, D_r \rangle$ and $va_s = \langle A_s, D_s \rangle$: if $va_r > va_s$ holds in VP and there is a path from va_r to va_s with length $\leqslant k$, then there exist a base activity $a_r \in A_r$ and a base activity $a_s \in A_s$ such that $a_r > a_s$ holds in BP.

The induction step must show that there exist a base activity $a_i \in A_i$ and a base activity $a_j \in A_j$ such that $a_i > a_j$ holds in VP, when the length of the path vp from va_i to $va_j \leqslant k+1$. Let va_h be a virtual activity on the path vp from va_i to va_j, where $va_h = \langle A_h, D_h \rangle$, $va_h \neq va_i$ and va_j. The length of the subpath of vp from va_i to $va_h \leqslant k$, since the length of $vp \leqslant k+1$. Besides, the length of the subpath of vp from va_h to $va_j \leqslant k$. Moreover, $va_i > va_h$ holds in VP and $va_h > va_j$ holds in VP. Now, there exist a base activity $a_i \in A_i$ and a base activity $a_h \in A_h$ such that $a_i > a_h$ holds in BP, according to the induction hypothesis, since $va_i > va_h$ holds in VP and there is a path from va_i to va_h with length $\leqslant k$. Similarly, there exist a base activity $a_h \in A_h$ and a base activity $a_j \in A_j$ such that $a_{h'} > a_j$ holds in BP. If $a_h = a_{h'}$, then $a_i > a_j$ holds in BP since both $a_i > a_h$ and $a_{h'} > a_j$ hold in BP. On the other hand, if $a_h \neq a_{h'}$, then $a_i > a_{h'}$ holds in BP, since a_h and $a_{h'}$ are members of va_h, a_i is not a member of va_h, and the ordering relations between a_i and all members of va_h are identical in BP, according to Definition 10(1c). Consequently, $a_i > a_j$ holds in BP since both $a_i > a_{h'}$ and $a_{h'} > a_j$ hold in BP. □

Lemma 4. *Consider a process-view* $VP = \langle VA, VD \rangle$, *where members of VA follow Definition* 10 *and members of VD follow Definitions* 11 and 12, *derived from a base process* $BP = \langle BA, BD \rangle$. *Let LP be a loop-derived sub-process of BP*; *let VLP be a loop-derived sub-process-view of VP*; *VLP corresponds to LP. For any two distinct virtual activities* va_i *and* va_j *in VLP*, $va_i = \langle A_i, D_i \rangle$ *and* $va_j = \langle A_j, D_j \rangle$: *if* $va_i > va_j$ *holds in VLP, then there exist a base activity* $a_i \in A_i$ *and a base activity* $a_j \in A_j$ *such that* $a_i > a_j$ *holds in LP.*

Proof. The proof is similar to the proof of Lemma 3 and is omitted. □

References

[1] D. Georgakopoulos, M. Hornick, A. Sheth, An overview of workflow management—from process modeling to workflow automation infrastructure, Distrib. Parallel Databases 3 (2) (1995) 119–153.

[2] F. Leymann, W. Altenhuber, Managing business processes as an information resource, IBM Systems J. 33 (2) (1994) 326–348.

[3] D. Georgakopoulos, H. Schuster, A. Cichocki, D. Baker, Managing process and service fusion in virtual enterprises, Inf. Systems 24 (6) (1999) 429–456.

[4] IBM Corp., MQ series workflow: concepts and architecture, 2001.

[5] Ultimus Inc., Ultimus 5.0 Product Guide, 2001.

[6] N. Krishnakumar, A. Sheth, Managing heterogeneous multi-system tasks to support enterprise-wide operations, Distrib. Parallel Databases 3 (2) (1995) 155–186.

[7] Workflow Management Coalition, Interface 1: Process definition interchange process model, Technical report WfMC TC-1016-P, Nov. 12, 1998.

[8] J.C.M. Baeten, W.P. Weijland, Process Algebra, Cambridge Tracts in Theoretical Computer Science, Vol. 18, Cambridge University Press, Cambridge, 1990.

[9] R. Milner, A Calculus of Communication Systems, Lecture Notes in Computer Science, Vol. 92, Springer, Berlin, 1980.

[10] L. Pomello, G. Rozenberg, C. Simone, A survey of equivalence notions of net based systems, advances in Petri Nets 1992, in: G. Rozenberg (Ed.), Lecture Notes in Computer Science, Vol. 609, Springer, Berlin, 1992, pp. 410–472.
[11] R.J. van Glabbeek, W.P. Weijland, Branching time and abstraction in bisimulation semantics, J. ACM 43 (3) (1996) 555–600.
[12] W.M.P. van der Aalst, A.H.M. ter Hofstede, Verification of workflow task structures: a Petri-Net-based approach, Inf. Systems 25 (1) (2000) 43–69.
[13] W. Sadiq, M.E. Orlowska, Analyzing process models using graph reduction techniques, Inf. Systems 25 (2) (2000) 117–134.
[14] F. Leymann, D. Roller, Production Workflow: Concepts and Techniques, Prentice-Hall, Englewood Cliffs, NJ, 2000.
[15] J.L. Gross, J. Yellen, Graph Theory and its Applications, CRC Press, Boca Raton, FL, 1999.
[16] A. Christie, Software Process Automation: The Technology and its Adoption, Springer, New York, 1995.
[17] S. Jablonski, C. Bussler, Workflow Management: Modeling Concepts, Architecture, and Implementation, International Thomson Computer Press, London, 1996.
[18] V. Gruhn, Business process modeling and workflow management, Int. J. Cooperative Inf. Systems 4 (2&3) (1995) 145–164.
[19] A.-W. Scheer, ARIS—Business Process Modeling, 2nd Edition, Springer, Berlin, 1999.
[20] G. Kappel, P. Lang, S. Rausch-Schott, Workflow management based on objects, rules, and roles, IEEE Bull. Technical Committee Data Eng. 18 (1) (1995) 11–18.
[21] D.C. Kung, The behavior network model for conceptual information modeling, Inf. Systems 18 (1) (1993) 1–21.
[22] G. Vossen, M. Weske, The WASA2 Object-oriented workflow management system, Proceedings of International Conference on Management of Data (SIGMOD), Philadelphia, USA, May 31–June 3, 1999, pp. 587–589.
[23] W. Weitz, Combining structured documents with high-level Petri-Nets for workflow modeling in internet-based commerce, Int. J. Cooperative Inf. Systems 7 (4) (1998) 275–296.
[24] K. Salimifard, M. Wright, Petri Net-based modeling of workflow systems: an overview, Eur. J. Oper. Res. 134 (3) (2001) 664–676.
[25] W.M.P. van der Aalst, The application of Petri Nets to workflow management, J. Systems Circuits, Comput. 8 (1) (1998) 21–66.
[26] W.M.P. van der Aalst, How to handle dynamic change and capture management information: an approach based on generic workflow models, Comput. Systems Sci. Eng. 15 (5) (2001) 267–276.
[27] M.P. Papazoglou, P. Riebbers, A. Tsalgatidou, Integrated value chains and their implications from a business and technology standpoint, Decision Support Systems 29 (4) (2000) 323–342.
[28] J. Yang, M.P. Papazoglou, Interoperation support for electronic business, Commun. ACM 43 (6) (2000) 39–47.
[29] K. Hiramatsu, K. Okada, Y. Matsushita, H. Hayami, Interworkflow system: coordination of each workflow system among multiple organizations, Proceedings of the Third IFCIS International Conference on Cooperative Information Systems (CoopIS'98), New York, USA, August 20–22, 1998, pp. 354–363.
[30] F. Lindert, W. Deiters, Modeling inter-organizational processes with process model fragments, Proceedings of the GI Workshop Informatik'99, Paderborn, Germany, October 6, 1999.
[31] Workflow Management Coalition, the workflow reference model, Technical report WfMC TC-1003, January 19, 1995.