Modelling and Analysis of Workflow Processes

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Abstract

Practical experience indicates that the definition of real-world workflow applications is a complex and error-prone process. Existing workflow management systems provide the means, in the best case, for very primitive syntactic verification, which is not enough to guarantee the overall correctness and robustness of workflow applications. The paper introduces a method for formal verification of workflow schemas (definitions). Workflow behaviour is modelled by means of an automata-based method, which facilitates exhaustive compositional reachability analysis. The workflow behaviour is checked against both safety and liveness properties, which can be either generic (applicable to all workflow schemas) or domain specific (applicable to a given schema). The analysis is performed by automated tools, which are accessible by designers who are not experts in formal methods.

1 Introduction

Workflow Management Systems provide automated support for defining and controlling various activities (tasks) associated with business processes [1, 2]. A *Workflow Schema* is used to represent the structure of an application in terms of tasks as well as temporal and data dependencies between tasks. A *Workflow Application* (or just *Workflow*) is executed by instantiating the corresponding workflow schema [3].

The aim of providing automated support for business processes is to reduce costs and flow times, to improve the robustness of the process and to increase productivity and quality of service [4, 5]. However, specifying a real-world workflow schema is a complex manual process, which is prone to errors. Incorrectly specified workflow schemas result in erroneous workflow applications, which, in turn, may cause dramatic problems in the organisation where they are deployed. Therefore, it is crucial to be able to verify the correctness of a workflow schema before it becomes operational.

Many commercial workflow management systems provide the means for some basic syntactic verification, while a workflow schema is designed. They check, for example, for the existence of inputs and outputs in task specifications. However, more thorough and rigorous analysis is required to ensure that the schema is correct [6]. For instance, we need to be able to check that the workflow eventually terminates, that there are no potential deadlocks, or that a certain path of execution is possible. This paper proposes a novel method for formal verification of workflow schemas, by means of *Labelled Transition Systems* (LTS). We propose a complete mapping of workflow entities to the LTS model and discuss analysis techniques for checking safety and liveness properties. Analysis is done by automated tools provided as part of the LTSA toolkit. LTSs and in particular the TRACTA approach followed here have been used extensively to model and analyse concurrent systems. It has been shown that the method is accessible and usable by practising engineers, who are not experts of model-checking techniques.

Due to the size and complexity of most real-world workflow schemas, any viable analysis method should follow an incremental (compositional) approach, which should be applied at each step of the design procedure. Experience shows that correctness by design is clearly preferable over approaches where correctness is verified after the design of the final workflow has been completed [7]. TRACTA addresses exactly these problems by enforcing a close integration of modelling and analysis with system design. In particular, *Compositional Reachability Analysis* (CRA) is used for modelling and analysis of system components as they are composed from other sub-components. CRA improves the computational complexity of analysis (together with minimisation techniques) and favours reusability of specifications. To the best knowledge of the authors, there is no other system that provides a satisfactory way for compositional/incremental verification of workflows.

The remainder of this paper is organised as follows. Section 2 provides an overview of the semantics of our workflow definition notation and outlines the requirements for verification in this context. In the same section, we also outline the TRACTA approach to compositional reachability analysis and argue about the suitability of the method to verification of workflow schemas. Sections 3 and 4 form the core of the paper. Section 3 proposes a complete and formal modelling, in terms of LTSs, of all workflow schema elements. Section 4 discusses the classes of safety and liveness properties that can be verified using the TRACTA techniques and the LTSA toolkit. In both sections, the theoretical concepts are illustrated by means of a case study: a workflow for business trip reservations. The paper is concluded (section 5) with a critical discussion of the proposed method and directions of future work.

2 Background

2.1 Defining workflow schemas

A workflow schema must be expressive enough to represent the structure of a business process. The schema represents a workflow application as a collection of tasks and their dependencies. A task is an application-specific unit of activity that requires specified input objects and produces specified output objects. There can be two types of dependencies between tasks: 1) *notification* dependencies indicating temporal (causal) relations; 2) *dataflow* dependencies indicating that a task requires some input (data) from another task. In the following, we present the principles for workflow schema definitions [8].

A task can start in one of several initial states and can terminate in one of several output states. Thus, a task is modelled as having a set of *input sets* and a set of *output sets*. In Figure 1, task t_3 is represented as having three input sets I_1, I_2, and I_3, and two output sets O_1 and O_2.

The execution of a task is triggered by the availability of an input set; only the first available input set will trigger the task. For an input set to be available it must have received *all* of its constituent input objects and notification dependencies. For example, in Figure 1, input set I_1 of task t_3 requires three dependencies to be satisfied: objects i_1, i_2 and i_3 must become available (dataflow dependencies). On the other hand, input set I_2 requires three dependencies to be satisfied: object i_1 must become available and two notifications, n_1 and n_2, must be signalled (notifications are modelled as data-less input objects). A given input can be obtained from more than one source (e.g., two for object i_1 in set I_1 of task t_3). If multiple input sources become available simultaneously, then one source is selected deterministically.

The notification dependencies are represented by dotted lines, for example, s_6 is a notification source for notification dependency n_1. A notification dependency may have more than one alternative sources too. For example, n_1 has alternative sources s_5 and s_6.

A task terminates producing output objects belonging to exactly one of a number of output sets (e.g. O_1 or O_2 for task t_3). An output set consists of a (possibly empty) set of output objects (o_2 and o_3 for output set O_1 of t_3 and null object for the output set of task t_2).

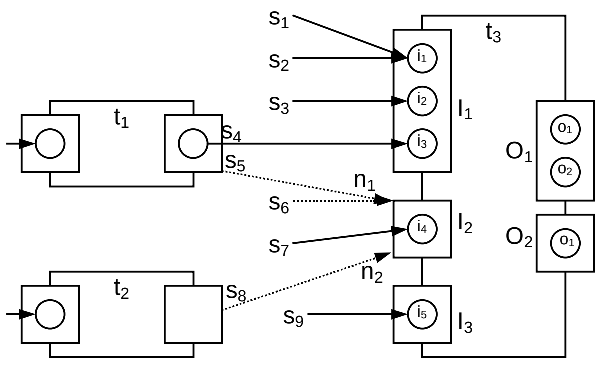


Figure 1. A workflow schema defining inter-task dependencies.

A workflow application consists of a number of inter-dependent tasks. A schema indicates how the constituent tasks are "connected". To allow workflow applications to be designed in a hierarchical way, tasks can be *composite*: they are realised as a collection of other, inter-dependent tasks. Therefore a task can be either primitive (implemented by some application service) or composite (consists of other primitive of composite tasks). A given input of the composite task may be the source of one or more internal inputs (data objects or notifications dependencies). Similarly, a given output may have more than one alternative sources. Figure 2 illustrates an example of a composite task called *Reservation*. The task provides the schema definition for a trip reservation workflow.

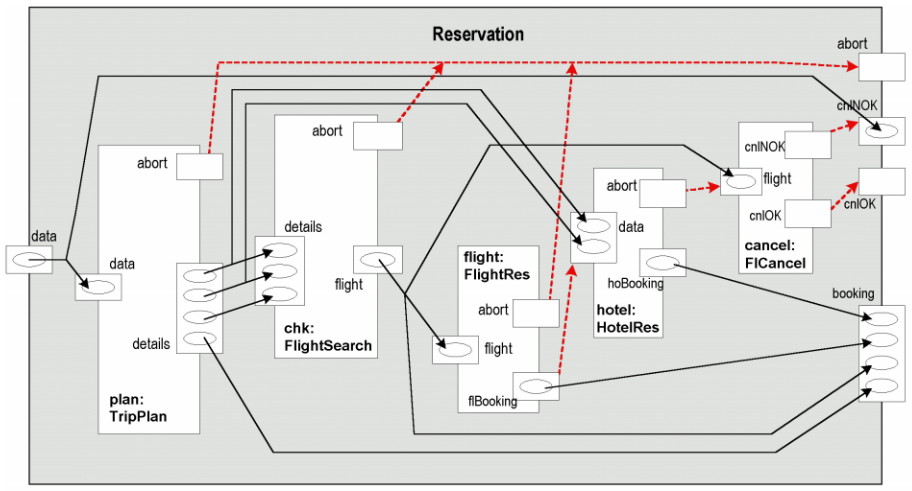


Figure 2. A composite workflow task.

Composite tasks provide the principal way of introducing reusability of workflow schema definitions. Figure 3 shows a composite task *BusinessTrip*, which reuses the definition of the *Reservation* task to define a workflow schema for a business trip reservation process. The latter two examples (tasks *Reservation* and *BusinessTrip*) will be used as case-studies for the rest of the paper, in order to illustrate the modelling concepts discussed.

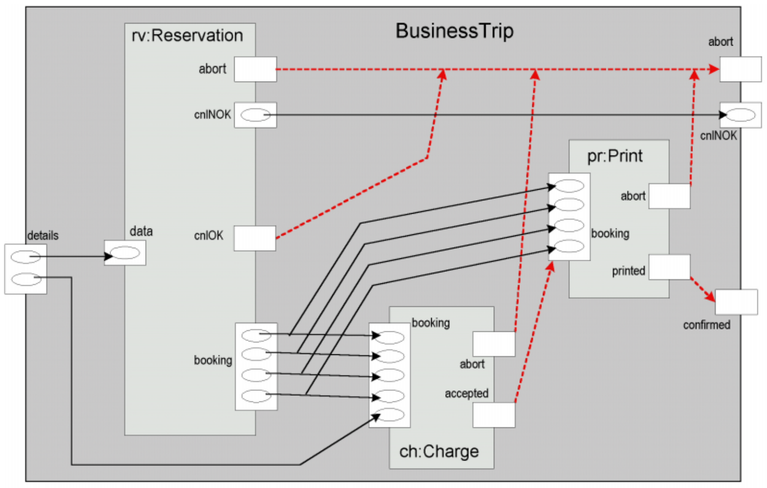


Figure 3. A composite workflow task containing a composite sub-task.

2.2 Requirements for a workflow verification method

Our experience with building large workflow systems has shown that it is common for errors to appear in the design of complex workflow schemas. These errors are typically detected only after the workflow is deployed and tested in practice. As it has been stressed in the introduction of the paper, it is very important for the designer to be able to apply a rigorous verification method on the schema and argue formally about the correctness of the resulting workflow instances. In this context, we have identified a number of requirements to be satisfied by any such verification method:

1. Have a solid mathematical foundation and allow for rigorous and formal analysis of both safety and liveness properties.
2. Perform exhaustive analysis at design-time (of the workflow schema) as well as interactive simulation of the workflow model.
3. Employ algorithms that are computationally efficient in order to be applicable to real-world systems. These algorithms should be supported by automated tools.
4. Follow a compositional approach in order to enable incremental analysis while the system is designed and to support re-use of specifications in multiple contexts.
5. Generate meaningful diagnostic information, in the form of execution traces, to indicate potential errors to the designer.
6. Use a comprehensible graphical representation for humans and also an equivalent well-defined and space-efficient formal notation for usage with the tools.
7. Be understandable and accessible by users who have no special expertise in the area of modelling and formal methods.

2.3 The TRACTA approach to behaviour modelling and analysis

The TRACTA approach has been extensively used for modelling and analysing concurrent and distributed systems [9-11]. It is based on the use of *Labelled Transition Systems* (LTS) for modelling the behaviour of system components and for expressing system properties.

In order to integrate analysis with other activities of software development, TRACTA has traditionally used software architecture to direct analysis. In general, the software architecture of a distributed system has a hierarchical structure [12, 13]. Therefore, TRACTA uses a compositional approach to modelling a system following the phases of hierarchical system design. Behaviour is attached to the software architecture by specifying a labelled transition system for each primitive component in the hierarchy (primitive is a system component which cannot be expanded to sub-components, at least for the sake of analysis). Following the terminology of traditional process algebras, the LTS of a primitive component is equivalent to a finite-state interacting process. An LTS contains all the reachable *states* and executable transitions (triggered by *actions*) of a process. The behaviour of composite system components is defined as the composition of the LTSs of their constituent components.

TRACTA exhaustively explores the reachable states of an LTS, a technique known as reachability analysis. The main disadvantage of this technique is state explosion. That is, the exponential relation between the system state-space and the number of its constituent components. TRACTA takes advantage of the hierarchical structure of the system in order to address this problem. As the system behaviour is composed in a bottom-up manner, internal details (actions) of a subsystem's behaviour are hidden and the subsystem is minimised, at intermediate stages of the analysis. In general, only a subset of the actions in a subsystem's LTS are of interest to external systems (processes) that interact with it. The key to the success of the technique is to hide as many internal actions as possible in each subsystem.

An LTS can be described either graphically or by explicitly specifying its alphabet, states, transition relation and initial state (as in traditional automata theory). However, such representations become impractical for systems with more that a few states. For this reason, TRACTA uses a simple process algebra notation called FSP (stands for *Finite State Process*) to specify the behaviour of components in a system [14]. FSP is not a different way of modelling a system. It is a specification language with well-defined semantics in terms of LTSs, which provides a concise way for describing LTSs. Each FSP expression can be mapped onto a finite LTS and vice versa.

Reachability analysis owes much of its popularity to the fact that it is fairly easy to automate. TRACTA is supported by the *LTSA software tool*, which provides for automatic composition, analysis, minimisation, animation and graphical display of system models expressed in FSP.

Primitive system components

Primitive system components are defined as finite-state processes in FSP using action prefix "`->`", choice "`|`" and recursion. If `x` is an action and `P` a process, then `(x->P)` describes a process that initially engages in the action `x` and then behaves exactly as described in `P`. If `x` and `y` are actions, then `(x->P|y->Q)` describes a process which initially engages in either of the actions `x` or `y`, and the subsequent behaviour is described by `P` or `Q`, respectively. The definition of a primitive component may use an *auxiliary* process. Actions can be parameterised with variables from a set of values; `(x[v:Values]`

`->R`) describes a process which engages in one of a set of possible actions `x[v]`, for `v ∊ Values` (set `Values` must be explicitly specified in the model).

FSP uses an *interface* operator ‘`@`’, which specifies the set of action labels which are visible at the interface of the component and thus may be shared (synchronisation points – used for interaction) with other components. It restricts the alphabet of the LTS to the actions *prefixed* by these labels. All other actions are “hidden” and will appear as silent “τ” (tau) actions during analysis, if they do not disappear during minimisation of the component. When it is more concise to describe what actions are hidden rather than which actions remain observable, the *hiding* operator “\” may be used, which is complementary to the interface operator.

Composite system components

Composite-component processes are defined in terms of other, non-auxiliary, processes. Their identifiers are prefixed with “`||`”. The process of a composite component does not define additional behaviour: it is simply obtained as the parallel composition of instances of the processes it is made of. Process instances are denoted as “*instance-name:type-name*”. The LTS of the instance is identical to that of the type, with action labels prefixed with the instance name. The instance name is not necessary if there is just one instance of a process in a given context. Composition expressions use parallel composition (`||`) together with operators such as re-labelling (`/`), action hiding (\) or interface (`@`). Communication is modelled by means of synchronisation of shared actions (the remaining actions are interleaved). Actions that correspond to interaction interfaces are re-labelled to a common name in order to be synchronised when behaviours are composed. Re-label specifications are of the form “new-label/old-label”.

```
set Doc = {x}

Printer = (request -> print[d:Doc]
   -> reset -> release -> Printer)
   \{reset}.


Spooler = (request -> Transfer),
Transfer =(submit[d:Doc] -> Transfer
      | release -> Spooler).

minimal
|| System =  (Printer || Spooler)
   /{print/submit}.
```

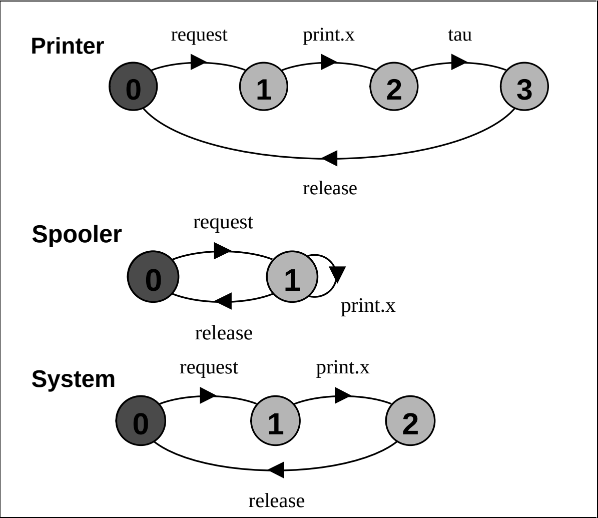


Figure 4. Modelling primitive and composite system components with TRACTA.

Figure 4 depicts the model of three system components, each represented by a process in FSP. Process `Printer` models a printer, a primitive system component; the `print` action is parameterised with values from set `Doc` and action `reset` is hidden from the visible process interface. The specification of process `Spooler` uses an auxiliary process `Transfer`. Finally, process `System` represents a composite component, which consists of one printer and one spooler instance (instance names do not have to be explicitly specified here, since we have just one instance of each process). In the parallel composition, actions `request` and `release`, which have the same name in both `Printer` and `Spooler`, are implicitly synchronised, while actions `print` and `submit` are explicitly synchronised by renaming `submit` to `print`. The figure illustrates the FSP specifications of the three processes as well as the corresponding LTS diagrams automatically produced by the LTSA tool. The `minimal` keyword enforces minimisation of the `System` process to hide any transitions labelled exclusively by tau actions. More details of the TRACTA approach will be shown when the actual modelling of workflow systems is discussed later on in the paper.

3 Workflow modelling

This section presents the proposed method for modelling workflow schemas, by means of the TRACTA compositional approach. The model of each schema consists of two parts. The first part is generic and is concerned with modelling elements that are common to every schema, such as input-output interfaces and techniques for representing dataflow and causal dependencies between tasks. The second part is application specific and is concerned with the model of actual tasks in the schema and their inter-dependencies. The models are presented in the form of FSP specifications and, when appropriate, as LTS diagrams produced by the LTSA tool.

3.1 Task interfaces

A task interacts with its environment through its *interface sets*. Interface sets consist of zero or more *data objects* (representing dataflow dependencies) and inbound and outbound *notifications* (representing causal dependencies). Interface sets model the common denominator of the behaviour of input and output sets of tasks.

- *An interface set is "available", if all its dataflow and notification dependencies are satisfied. When an interface set is available, then all of its constituent objects and outbound notifications are also available.*

An interface *object* can perform `input` and `output` actions, reflecting the fact that the object receives and outputs data, respectively. To model the fact that an interface becomes available when *all* its constituent objects are available (a logical AND operation), we use an action `available`, on which all objects in an interface set need to synchronise. An object can only perform `available` after performing action `input`. Therefore, the behaviour of an object with identification `ID` (to uniquely identify it in the set) is modelled as follows:

```
Object (ID=1) = (input[ID] -> available -> output[ID] -> STOP).
```

Action `available` is also used to make sure that all inbound notifications are received before an interface set becomes available and also, that outbound notifications are provided only after the interface set becomes available:

```
InNotification (ID=1) = (inNotify[ID] -> available -> STOP).
OutNotification = (available -> outNotify -> STOP).
```

An interface set is then modelled as the parallel composition of a set of objects and inbound and outbound notifications. If an interface set does not contain any objects, and has no notification dependencies, it is unconditionally available, as modelled by the following default process:

```
Default = (available -> STOP).

|| Iface (Objs=1, INotfs=1, ONotfs=1) =
       if (ONotfs >= 2) then
              Iface_Problem
       else (   if (Objs > 0) then
                     (forall [i:1..Objs] Object(i))
              || if (INotfs > 0) then
                     (forall [i:1..INotfs] InNotification(i))
              || if (ONotfs > 0) then
                     OutNotification
              || if (Objs == 0 && INotfs == 0 && ONotfs == 0) then
                     Default
       ).

Iface_Problem = (erroneous -> ERROR).
```

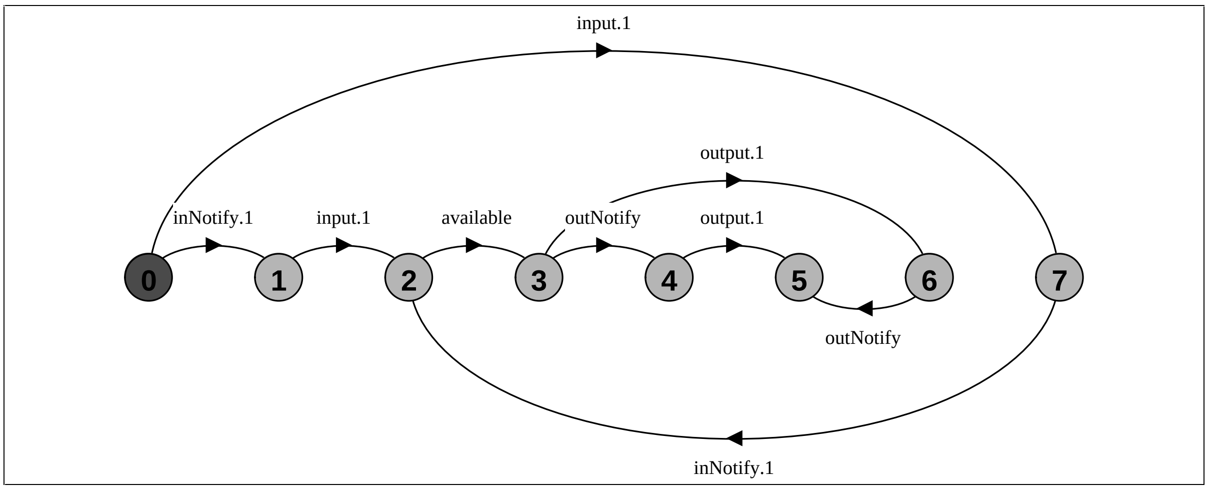


Figure 5: LTS of an interface set, with one object, one in- and one out- notification.

An interface produces at most one outbound notification (which can be bound to more than one task). Thus, no identifier is required for these type of notifications. For the same reason, a process `Iface_Problem` is introduced to model a transition to an error state, if an interface instance is specified with more than one outbound notification. Figure 5 illustrates the LTS of an interface with one object, one inbound and one outbound notification. The general model of an interface set that we have described above will be adjusted to reflect input and output sets of primitive or composite components, as we show in the following sections.

3.2 Primitive tasks

Primitive tasks either have no internal structure or their internal structure is not provided in the workflow schema description. The main entities of a primitive task that need to be modelled are its interfaces, qualified as *input* and *output sets*. They are called abstract sets (`AbsInputSet` and `AbsOutputSet`) and they are modelled as interfaces that have zero notifications. The reason is that, in the general case, a task should be modelled in a reusable way: the designer has no knowledge of the context where the task may be instantiated in. Therefore, at this stage, no information can be provided about potential notification dependencies of input sets, or notification dependencies on the output sets of the task.

Moreover, information that is concerned with the outputs of input sets and the inputs of output sets, is encapsulated within the model of these tasks. The corresponding actions are hidden appropriately. This is achieved by keeping visible only actions prefixed with labels `input` and `ready` for input sets, and `output` and `enabled` for output sets. In addition, action `available` of the `Iface` process is renamed to `ready` in the case of input and to `enable` in the case of output sets.

The prefix "minimal" is added to the processes to make sure that, during the generation of the model, our tools will not only hide these actions but will also minimise the corresponding LTSs. Minimisation results in a more compact but behaviourally equivalent model. Figure 6 illustrates the LTS for process `AbsInputSet` in three forms: without action hiding (but after renaming action `available` of `Iface` to `ready`), after hiding action `output` by explicitly making only actions `ready` and `input` visible, and after hiding with enforced minimisation.

```
minimal
|| AbsInputSet (Objs=1) =  (Iface(Objs, 0, 0))
                                 / {ready/available}
                                 @ {ready, input}.

minimal
|| AbsOutputSet (Objs=1) =       (Iface(Objs, 0, 0))
                                 / {enable/available}
                                 @ {enable, output}.
```

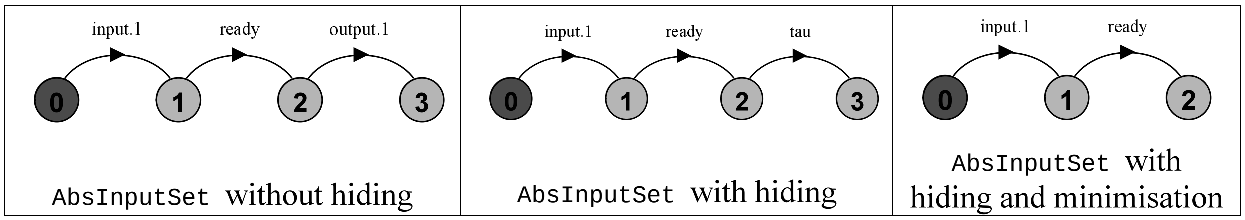


Figure 6. The model of process `AbsInputSet`.

A primitive task's behaviour is dictated by two rules:

- *The execution of a task starts as soon as one of its input sets is available.*
- *When the execution of a task completes, exactly one of its output sets is available.*

The above two rules also capture the causal dependency between a task's input and output sets. This behaviour pattern is common to all primitive tasks and is modelled by the process `AbsTaskImpl`. This process also models the fact that, even if more than one input set is available, just one is selected by the internal task behaviour and exactly one output is produced.

```
AbsTaskImpl (InSets=1, OutSets=1) = ( ready[i:1..InSets] -> Execute ),
Execute = ( enable[o:1..OutSets] -> STOP ).
```

A specific primitive task is then defined as the parallel composition of its input and output sets with the above default implementation process. For example, the primitive task `TripPlan` of Figure 2, with one input set (named `data`) and two output sets (named `abort` and `details`), is modelled as shown below. The renaming reflects the bindings of the task's interfaces to `AbsTaskImpl`.

```
|| TripPlan = (     AbsTaskImpl(1, 2)
                    ||     data:AbsInputSet(1)
                    ||     abort:AbsOutputSet(0)
                    ||     details:AbsOutputSet(4)
               )
               /{  data.ready/ready[1],
                   abort.enable/enable[1],
                   details.enable/enable[2] }.
```

3.3 *Composite tasks*

Composite tasks are constructed out of a number of constituent task (sub-task) instances. Sub-tasks are either primitive or composite tasks themselves. When a composite component is specified, the data objects of its input set(s) are bound to objects of input sets of sub-tasks. The objects of its output sets are bound to objects of output sets of sub-tasks. Similarly, in the context defined by the composite task, there may be notification dependencies from the input sets of the composite to input sets of sub-tasks and from output sets of sub-tasks to output sets of the composite task. For example, in the case of the workflow schema of Figure 2, the composite task `Reservation` consists of a number of interconnected sub-task instances, such as `plan` of type `TripPlan` (denoted `plan:TripPlan`), `chk` of type `FlightSearch` and `cancel` of type `FlCancel`. Among other dependencies, the (single) data object of input set `data` of `Reservation` is bound to the object of input set `data` of `plan:TripPlan` and there is a notification dependency from the output set `cnlOK` of sub-task `cancel:FlCancel` to the output set `cnlOK` of `Reservation`.

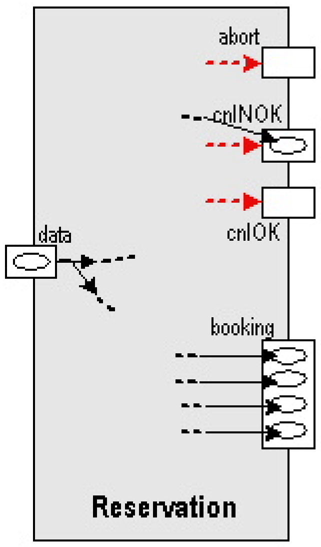
The context of a composite task specifies the internal dependencies between its constituent tasks. However, incoming notification dependencies to the composite's own input sets and outgoing notification dependencies from the composite's output sets are not known in this context. The aim is to achieve reusability of the composite task's model, by making it context independent. This principle is captured in the specifications of the "external" input and output sets of composite tasks. An `InputSet` is an interface set with no input notifications and an `OutputSet` is an interface set with no output notifications. In order to differentiate between input and output sets, `Iface`'s `available` action is renamed to `ready` and `enable`, respectively.

```
|| InputSet (Objs=1, ONotfs=1) =
      if (Objs ==0 && ONotfs==0) then Iface_Problem
                             else (Iface(Objs, 0, ONotfs))
      / {ready/available}.

|| OutputSet (Objs=1, INotfs=1) =
      if (Objs ==0 && INotfs==0) then Iface_Problem
                             else (Iface(Objs, INotfs, 0))
      / {enable/available}.
```

The conditional specification in the above model states that: 1) external input set must have at least one (boundable) data object or one outgoing notification; 2) an external output set has at least one data object or at least one incoming notification. Process `Iface_Problem` is again used to model a transition to an error state, if either of the above conditions is not satisfied. Composite task `Reservation` has one such "external" input set and four output sets. Figure 7 illustrates a general diagram of the task interfaces and the corresponding model.

In the case of composite tasks, we have, again, to model the fact that exactly one input set is selected even if more than one is available and exactly one output set is enabled when the task terminates (both primitives are enforced by the execution environment). The later is modelled by processes `InSelector` and `OutSelector`, instances of which are used together with the necessary action renaming in the model of the composite component.



```
|| Reservation = (
   /* Selectors of interface sets ...*/
     InSelector(1) || OutSelector(4)
   /* Interfaces ... */
     /* Input sets */
       || data:InputSet(1, 0)
     /* Output sets */
       || abort:OutputSet(0, 1)
      || cnlNOK:OutputSet(1, 1)
      || cnlOK:OutputSet(0, 1)
      || booking:OutputSet(4, 0)
    ...
   ) /{ ... }.

   InSelector (InSets=1) =
                  (ready[i:1..InSets] -> STOP).
   OutSelector (OutSets = 1) =
                  (enable[i:1..OutSets] -> STOP).
```

Figure 7. "External" input and output sets of a composite component.

Another problem that has to be addressed, when composing task instances together, is the way that notification dependencies between these tasks are modelled. As it has been already discussed, the incoming and outgoing notifications of a task's external interfaces are not known when the task is specified (whether primitive of composite itself). That was a modelling decision in favour of specification reusability. Thus, when instances of tasks are interconnected within the context of a composite task, two additional generic processes, `ContextOutNotfs` and `ContextInNotfs` are used to provide the "glue" for this composition. In particular, these processes are used to add notification dependencies to sub-tasks, as required by the context (composite task) where the sub-tasks are instantiated. Their models are based on those of abstract input and output sets, since they introduce conditions for an input to become ready or provide outputs, in the form of notifications, as soon as an output set is enabled. The re-namings introduced simply re-label output actions to `outNotify` ones and input actions to `inNotify` ones. Recall that we can have only a single outbound notification per output set.

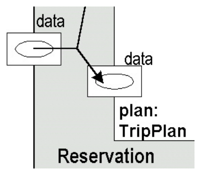
```
|| ContextOutNotfs =    AbsOutputSet( 1 )
                              / { outNotify/output[1] }.

|| ContextInNotfs (INotfs=1) =   AbsInputSet( INotfs )
                              / { inNotify/input }.
```

In other words, all input and output sets, whether abstract (when they belong to primitive tasks) or not (when they belong to non-primitive tasks), may need to be qualified with notifications when their tasks are put in a context. For example, the model of task `Reservation` consists of the parallel composition of five constituent task instances, together with their context-dependent notification models:

```
|| Reservation = (
   ...
   /* Constituent tasks ... */
   || plan:TripPlan       || plan.abort:ContextOutNotfs
   || chk:FlightSearch    || chk.abort:ContextOutNotfs
   || flight:FlightRes    || flight.abort:ContextOutNotfs
                          || flight.flBooking:ContextOutNotfs
   || hotel:HotelRes      || hotel.data:ContextInNotfs(1)
                          || hotel.abort:ContextOutNotfs
   || cancel:FlCancel     || cancel.flight:ContextInNotfs(1)
                          || cancel.cnlNOK:ContextOutNotfs
                          || cancel.cnlOK:ContextOutNotfs
   ) / {
         data.ready/ready[1], abort.enable/enable[1],
         cnlNOK.enable/enable[2], cnlOK.enable/enable[3],
         booking.enable/enable[4],
       ... }
```

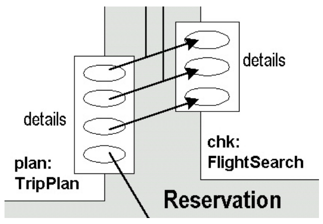
The implementation of composite tasks is modelled by the appropriate bindings between the interfaces of the constituent sub-tasks. In the case of the `Reservation` task, the dataflow dependency between the `data` object of `Reservation`'s (external) input set and the object of the input set of task `plan:TripPlan` is modelled by the renaming of Figure 8.



```
|| Reservation = ( ... )
   / {data.output[1]/plan.data.input[1], … }
```

Figure 8. Dataflow dependencies between external and sub-task input objects.

The dataflow dependency between three of the objects of the `data` output set of `plan:TripPlan` and the `data` input set of `chk:FlightSearch` are modelled by a similar renaming of all the corresponding data objects, as shown in Figure 9.



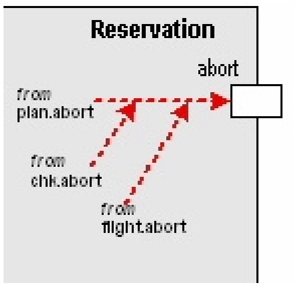
```
|| Reservation = ( ... )
   / { ...,
      plan.details.output[1]/chk.details.input[1],
      plan.details.output[2]/chk.details.input[2],
      plan.details.output[3]/chk.details.input[3]
     , ... }
```

Figure 9. Dataflow input dependencies between data objects of sub-tasks.

Dataflow dependencies are specified on a per data object basis. A single data object may be the source of more than one dependencies. For example, the first two objects of the details output set of `plan:TripPlan` are also bound to an input set of the `hotel:HotelRes` task:

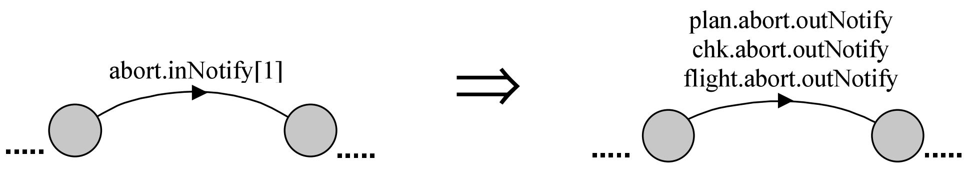
```
|| Reservation = ( ... )
   / { ...,  plan.details.output[1]/hotel.data.input[1],
         plan.details.output[2]/hotel.data.input[2], ... }
```

A given interface set or data object may have more than one alternative input sources. Availability of just one of the input sources is enough to enable the set or object, accordingly. Alternative dependency sources are modelled by means of *relational relabelling*. In our example, the `abort` output set of `Reservation` can be enabled by a number of alternative sources: `plan.abort`, `chk.abort` and `flight.abort`. The corresponding action `abort.inNotify[1]` is relationally renamed to `plan.abort.outNotify`, `chk.abort.outNotify` and `flight.abort.outNotify`, as shown in Figure 10(a). This relabelling states that a transition labelled `abort.inNotify[1]` in the LTS of the "external" output set `abort` is, now, performed when *any* of the other three transitions occurs. The corresponding transformation of the LTS is shown in Figure 10(b).



```
|| Reservation = ( … )
   / { ... ,
           { plan.abort.outNotify,
             chk.abort.outNotify,
             flight.abort.outNotify
           } /abort.inNotify[1]
      ,... }
```

(a) Modelling alternative input sources for notification dependencies.



(b) LTS transformations due to relational relabelling.

Figure 10. Relational relabelling used to model alternative input sources.

From the above discussion, it is clear that the procedure to create the model of a workflow schema from the actual workflow description can be easily supported by automated tools. We are currently developing a compiler that parses a correct schema description and produces the model of the schema, in FSP. The latter can be either saved as a re-usable model module or be directly fed to the LTSA tool.

4 Workflow analysis

The LTSA tool supports the TRACTA approach for analysis of systems modelled as LTSs. This section describes how to customise generic LTS analysis techniques for the domain of workflow systems.

4.1 Interactive simulation

A practical first step in checking a process is to simulate its behaviour. Simulation is performed as a user-controlled animation of the process. For composite processes, the LTS of their behaviour is not composed first. The method does not, as a result, suffer from state explosion. The LTSs of the components of the process are used to determine the current state of the process, as well as which actions are enabled at that state. The enabled actions are the "ticked" actions in the "animator window". When the user selects one of these actions, the process transits to the corresponding next state. The LTSA tool highlights the transitions on the LTS diagrams of the component processes and presents the corresponding system trace.

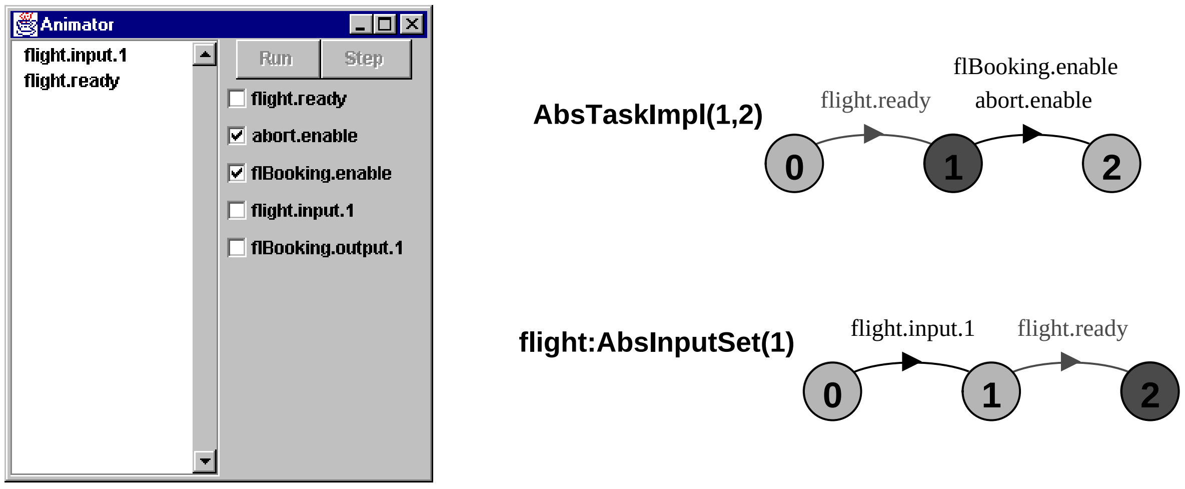


Figure 11: Interactive simulation of task type FlightRes.

Figure 11 illustrates the interactive simulation of the flight reservation task `FlightRes` (see Figure 2). We can see that after the input to the task has been provided, its input set `flight` is ready. Action `flight.ready` is performed synchronously by processes `flight:AbsInputSet(1)` and `AbsTaskImpl(1,2)`. Since this is a primitive task, the outputs become available, as soon as an input set is ready. In this case, when actions `abort.enable` and `flBooking.enable` become available, users may select which output to enable, according to the scenario they wish to check.

Interactive simulation provides an intuitive way for the system designers to experiment with different execution scenarios. However, in the general case, interactive simulation cannot establish the correctness of a real system, since designers cannot simulate all its possible execution scenarios. For that reason, techniques are required for rigorously checking the models of workflow systems.

4.2 Properties

The model-checking techniques associated with TRACTA can be used to check a workflow system exhaustively, against both generic and domain-specific properties. When a property is violated, our tools provide a *counterexample*. Counterexamples are a useful guide to debugging a model, since they describe executions of the system that violate some desired property.

Generic properties: deadlock

The LTSA identifies deadlock states in the LTS of a process, as states with no outgoing transitions. Reachability of such states is checked by default for every process in the system. This is because LTSA has been mainly aimed at reactive models that exhibit non-terminating behaviours. A typical way of dealing with terminating executions is to add a looping transition to each terminating state of a system (that is, a transition from the state back to itself). For workflow tasks that are expected to terminate, we provide a generic process called `ValidTaskTermination`, which models the fact that a valid terminating state of a task is one where some output of the task has been enabled:

```
ValidTaskTermination = (out_enabled -> TERM),
TERM = (term_ok -> TERM).
```

When composed with a task that we wish to check for deadlock, this process will add looping transitions to the valid terminating states of the task. In this way, only real deadlock states will have no outgoing transitions in the resulting LTS.

For example, to check that no execution of the `Reservation` task deadlocks, we compose the task process with the `ValidTaskTermination` process, as follows:

```
|| Complete_Reservation =
    ( Reservation || reservation:ValidTaskTermination)
    / { {abort.enable, cnlNOK.enable, cnlOK.enable, booking.enable} /
                                              reservation.out_enabled}.
```

The generic `ValidTaskTermination` has been instantiated with the name of task `Reservation`, to which it refers. Relational relabelling is also applied so that the `ValidTaskTermination` process transits to its terminating state whenever *any one* of the outputs of the `Reservation` task is enabled. In this way, valid terminating states of process `Complete_Reservation` will have looping transitions labelled with action `reservation.term_ok`. Indeed, the LTSA tool does not detect any deadlocks in process `Complete_Reservation`:

```
States Composed: 120 Transitions: 254 in 0ms
No deadlocks/errors
```

Generic properties: safety

In TRACTA, safety property violations are identified by the reachability of a special "error state", represented as state -1 in our LTSs. The error state has special semantics [10]. Firstly, it never has any outgoing transitions, reflecting the fact that there is no meaning in exploring a system after a safety violation has occurred. Moreover, in the context of parallel composition, local errors are propagated globally. By this we mean that if any component of a global state is an error state, then this global state is also an error state. The error state may be introduced in two ways in an LTS model:

1. *explicitly*, by means of some transition to the auxiliary process `ERROR`.
2. *implicitly*, by means of some safety property process added as a component of a system.

An example of an explicitly introduced error state can be found in process `Iface_Problem` discussed earlier. Safety properties are specified as FSP primitive processes, whose definition is prefixed with the keyword “property”. A property process with alphabet *A* describes *all* the traces from *A* that satisfy the property that it expresses. The LTS that our approach creates for such a process is *complete*, and has the characteristic that any trace from *A* that does not satisfy the property leads to the error state. For example, assume the following property:

```
property A_then_B = (a -> b -> STOP).
```

This property asserts that action `b` can only occur after action `a`, after which none of these actions is allowed to occur again. The corresponding LTS is illustrated in Figure 12. Note that property LTSs are composed with the components to which they refer. Then a system satisfies the properties that have been introduced to it, if the error state is not reachable in this system's LTS [10].

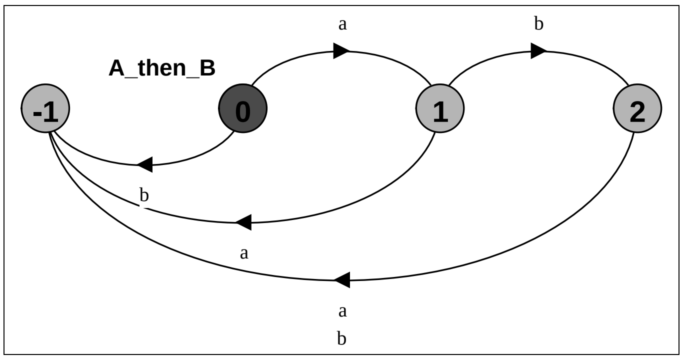


Figure 12: LTS for property `A_then_B`

A fundamental requirement that models of composite tasks have to be checked against is that the output produced by a task causally depends on the input that triggers its execution. The latter requirement is expressed by means of a safety property:

```
property Task_InOut_Relation = ( input_ready -> output_enable -> STOP ).
```

Property process `Task_InOut_Relation` is composed with process `Complete_Reservation` in order to check for potential violations of the property in the non-blocking version of the reservation task. Figure 13 illustrates the LTS for property `Task_InOut_Relation`, after relational relabelling is applied. It specifies, that if *any* one of the input sets (just `data` in our example) is enabled, then (and only then) *any* one of the output sets may be enabled by the corresponding task; any behaviour that does not conform to this pattern leads to an error state.

```
|| Check_InOut_Reservation =
(Complete_Reservation      || Task_InOut_Relation)
/ {  data.ready / input_ready,
     { abort.enable, cnlNOK.enable, cnlOK.enable, booking.enable}/ output_enable
  }.
```

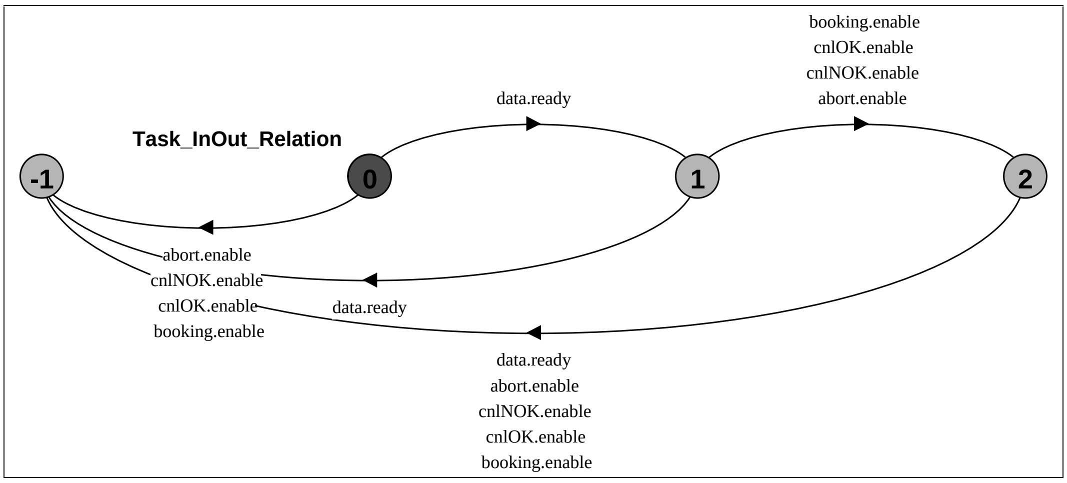


Figure 13. LTS of property `Task_InOut_Relation`.

Another typical requirement for any workflow schema is that each of its constituent tasks plays a role in the workflow. By this we mean that, for each task, there must exist at least one execution of the workflow where this task is triggered, i.e. where one of this task's input sets becomes ready. To check this for some task T, we introduce a property `PathsToSubtask` to the model, which states that no input set of T ever becomes ready. If our analysis tools return a counterexample, it means that indeed, there exists some execution where T is triggered, as desired. If the LTSA detects no violations, it means that T never plays any role in the context of the specific workflow. The generic form of property `PathsToSubtask` is the following:

```
property PathsToSubtask = STOP + {reachable}.
```

Here, action `reachable` (explicitly added to the alphabet of the property) expresses the fact that a task is triggered. In the context of each task, `reachable` is relationally relabelled to the set of ready actions corresponding to the task's input sets. For example, we proceed as follows to check that task plan is triggered in at least one execution of `Complete_Reservation`:

```
|| ExistPathsToPlan = ( Complete_Reservation || PathsToSubtask)
                        / { plan.data.ready/reachable }.
```

The LTSA tool returns the following result:

```
Trace to property violation in PathsToSubtask:
       data.input.1
       data.ready
       data.output.1
       plan.data.ready
```

The counterexample gives the prefix of an execution of `Complete_Reservation` where task `Plan` is triggered (`plan.data.ready`).

Generic properties: liveness

In our approach, a progress property "`progress P = {actions}`" requires that, in any infinite execution of a target system, at least one of the actions in set `{actions}` occurs infinitely often [11]. We use the following progress property to check that task `Complete_Reservation` eventually terminates (enables some output):

```
progress RESERVATION_TERM = {reservation.term_ok}
```

As discussed earlier, "`term_ok`" looping transitions distinguish the valid termination states of a task. By checking that action `term_ok` is performed infinitely often in any infinite execution of the task, we basically check that every execution of the task eventually terminates.

In the workflow models presented in this paper, a system that has no deadlocks trivially satisfies any such progress property. Progress properties are of particular interest in the case where the behaviour model of the resources used for the execution of each primitive task are also introduced in the overall system model. The latter is an ongoing research issue and is further discussed as part of the future work directions in section 5.

Domain-specific properties

In addition to checking generic properties of workflows, our techniques may be used for properties that refer to the particular workflow under analysis. Some examples are briefly described in this section.

- `Correct_Booking` asserts that booking is enabled only if both a flight and a hotel have been booked, and they have been booked in this order.

```
property Correct_Booking =  (    flight.flBooking.output[1] ->
                                 hotel.hoBooking.output[1] ->
                                 booking.enable -> STOP ).
```

- `Correct_Abort` asserts that, if any of the tasks `plan`, `chk`, or `flight` aborts, then the only possible outcome is an abort.

```
property Correct_Abort = No_Abort_Seen,
No_Abort_Seen =
( {cnlNOK.enable, cnlOK.enable, booking.enable} -> No_Abort_Seen
 |{plan.abort.enable, chk.abort.enable, flight.abort.enable} ->
                                                      Abort_Seen),
Abort_Seen = (abort.enable -> STOP).
```

- `Adds_To_Abort` additionally checks, that no task is triggered (i.e. no input set becomes ready) subsequently to any abort action.

```
property Adds_To_Abort = No_Abort_Seen,
No_Abort_Seen =
({plan.data.ready, chk.details.ready, flight.flight.ready,
                                    hotel.data.ready} -> No_Abort_Seen
|{plan.abort.enable, chk.abort.enable, flight.abort.enable} -> STOP).
```

In TRACTA, any number of properties may be checked *simultaneously* on a system. All the properties of interest can be composed with the process to be analysed; reachability of the error state is then checked. We can even compose properties amongst themselves, before they are applied to a process. The following example shows how properties `Correct_Abort` and `Adds_To_Abort` are composed, before they are applied, together with `Correct_Booking`, to process `Complete_Reservation`.

```
|| Strict_Abort_Check = (Correct_Abort || Adds_To_Abort).

|| Check_All = (  Complete_Reservation
                || Correct_Booking
                || Strict_Abort_Check).
```

4.3 Modularity and Abstraction

After checking thoroughly that a task satisfies its requirements, the behaviour of the task may be abstracted before re-using it in some other context. The only actions that need to be visible by the context of a task are actions related to its interfaces. Specifically, the interface of an abstracted task consists of the input actions of its input sets and the output actions of its output sets. Additionally, the ready actions of input sets and enabled actions of output sets must also be exposed, in order to be able to add notifications to and from the task when the latter is introduced in a context. All remaining actions are turned to the unobservable action τ (tau). The LTS of the task is then minimised, typically resulting in a smaller LTS. For example, the `Complete_Reservation` task is abstracted as follows:

```
minimal
|| AbstractReservation = ( Complete_Reservation )
          @ { data.input, data.ready,
              abort.enable, abort.output,
              cnlNOK.enable, cnlNOK.output,
              cnlOK.enable, cnlOK.output,
              booking.enable, booking.output
            }.
```

The size of the LTS of the reservation task is thus reduced to 26 from 120 states. Therefore, the modular approach for modelling and checking components advocated by our techniques can also reduce state explosion, which is the main inhibiting factor of exhaustive analysis methods.

5 Discussion and conclusions

The paper proposes a method for modelling and verifying workflow schemas, in lines with the TRACTA approach, which satisfies the fundamental requirements that have been set in section 2.2. It is a mature method that has been extensively used for model checking of complex concurrent and distributed systems. It uses a solid automata-based theory to allow exhaustive analysis on the static model of a system, at design time.

The TRACTA approach is fully automated within the LTSA toolkit. The algorithms employed for process composition, action hiding and minimisation are computationally efficient and scale well for real-world workflow schemas. In addition, LTSA provides a graphical representation of LTSs and an animation facility for simulating the execution of the model. Diagnostic information is presented in the form of counter examples: traces of execution that lead to violation of a desired property. The graphical user interface of LTSA facilitates the use of the method by designers that are not experts in formal methods. In fact, with an automated production of the model from the workflow schema definition (which is currently under development), the workflow designers will not have to write any FSP code apart from expressing the task properties they wish to analyse.

However, the feature of TRACTA that makes it particularly suitable for behaviour analysis of workflow schemas is *compositionality*. TRACTA traditionally follows a compositional approach to modelling and analysis, in order to address the state explosion problem which is inherent to all exhaustive reachability analysis techniques. We have exploited this feature, by making the models of tasks to be context independent and re-usable. Therefore, designers can check the model of their system in an incremental manner, while the system is designed. Design errors can be spotted early in the design and right in the components (tasks) where they occur.

The lack of compositionality is the main weakness of the *Woflan* system, according to its designers [7]. Woflan is a verification tool that uses a special type of Petri-nets to model and analyse the behaviour of workflow processes. Mappings from several proprietary workflow notations to the Woflan model have been devised and the tool has been extensively used in academic environments. Errors in the model are reported in the form of “behaviour error messages”, similar to our “counterexample traces”. The main advantage of the system is the theoretical robustness of the Petri-Net models and the clear representation of workflow state by token-based Petri-nets. However, the system lacks a means for visual representation of the model or the produced output (behaviour error messages). In addition, Woflan can only handle systems with up to 10^5 states. In comparison, LTSA can typically handle LTSs with more than 10^6 states, which may correspond to a system that is several orders of magnitude larger, before minimisation.

There are a number of directions we are planning to follow in order to extend the work presented in this paper. Although the proposed modelling method has been illustrated by means of a specific workflow notation, it is generic and product independent. To justify this claim, we are planning mappings for other proprietary notations used by commercial workflow management systems. In addition, the proposed method has to be extended with a generic model of recursive tasks (tasks that can trigger new instances of their own type), a common pattern in business processes.

The work presented in this paper focuses on the modelling and analysis of workflow schemas, irrespectively of the environment in which schemas are instantiated and executed. Such models can be enriched with the behaviour of system resources used for the enactment of workflow instances. Analysis of the extended models can then ensure that workflow specifications are consistent with the constraints set by the execution environment. We are currently investigating what are the required abstractions for modelling system resources in this setting.

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