# Using Timed Model Checking for Verifying Workflows

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## Abstract

The correctness of a workflow specification is critical for the automation of business processes. For this reason, errors in the specification should be detected and corrected as early as possible - at specification time.

In this paper, we present a validation method for workflow specifications using model-checking techniques. A formalized workflow specification, its properties and the correctness requirements are translated into a timed state machine that can be analyzed with the UPPAAL model checker. The main contribution of this paper is the use of timed model checking for verifying time-related properties of workflow specifications.

Using only one tool (the model checker) for verifying these different kinds of properties gives an advantage over using different specialized algorithms for verifying different kinds of properties.

**Keywords:** business process modeling, workflow, timed workflow specification, timed model checking, verification

## 1 Introduction, Related Work

In recent years, interest in business process automation has raised. One reason for this is that the concept of web services allows integrating web-based applications using open standards.

Developing a large system using web services starts with specifying the flow of control and information between these services - the workflow. This task should be done by domain experts. Different business process definition languages have been developed for specifying workflows, the most important ones are BPML, BPEL4WS, XPDL and UML2 activity diagrams. An increasing number of software tools abstract from the syntax of the business process definition language, allowing the business process analysts who specify the workflow to use a graphical notation (for example BPMN).

It should be possible to eliminate errors (like deadlocks or missed deadline constraints) in a workflow specification at specification time. Model checkers are sophisticated tools that are able to find exactly this kind of errors for a given system. What remains to do is to translate the workflow specification and the requirement we are interested in into the input language of a model checker.

Our paper shows how this "translation" can be done. Similar approaches were proposed by several other authors: [1] starts with an informal description of a business process. This description is being translated into the input language of the NuSMV model checker which can check basic properties like liveness and reachability. [2] checks various properties of business process specifications modelled in Testbed, a framework for business process reengineering. The business process specification can be defined by business process analysts using the Testbed tool, while the model checking must be done outside the tool by model checking experts. A follow-up paper [3], identifies some patterns of properties for business process specifications. Queries about these patterns are transformed automatically into an LTL formula, allowing people who are not familiar with the details of model checking to test properties of the busi-

*The Chair of Applied Telematics / e-Business is endowed by Deutsche Telekom AG ness process specification based on these patterns. [4] translates business process models defined in the XPDL language into the input language of the SPIN model checker in order to check their properties.

In all these publications, the properties than can be checked by a model checker, depends on logical order between activities, not on their timing. Other than these existing approaches, we take into account time-related properties (deadlines etc.).

We give an example for checking very different workflow properties: structural correctness, resource constraints, deadlines and dependences between different activities. In the overview below, we will refer to algorithms that allow to check these different classes of properties. The main contribution of this paper is to exploit only *one* tool for checking the different properties instead of using one algorithm to check the structural correctness, a second one for verifying the deadlines and other ones for reasoning about deadlocks, reachability or resource conflicts.

Scheduling of activities under resource constraints is a well-studied problem in operations research, known as *Resource Constraint Project Scheduling Problem* (RCPSP). The general problem - finding a feasible schedule for a set of activities such that the time for completing the project is minimized - has shown to be NP-hard [5], therefore different heuristic algorithms have been suggested for solving it [6]. Finding resource conflicts in a given workflow is much easier than solving the RCSP. [7] presents an algorithm to find such conflicts. (Our example workflow is based on the example used in this paper.) This is done by simply finding the earliest starting time and the latest completion time of each activity. However, the dependencies between the activities are not taken into account which leads to many false positives. Our model checking approach gives a more accurate result than [7].

[8] discusses the use of timed automata for solving the scheduling problem, which is also the key idea for our model-checking approach. [9] has expanded the net diagram technique PERT to ePERT which can be used for workflow specifications.

Structural correctness can be verified using graph analyzing techniques [10, 11], which require the use of special-purpose nontrivial algorithms. Graph analyzing techniques can also be used for answering "basic questions" about reachability and dependence between activities ("Will a receipt be sent for every order?", "Is it guaranteed that no receipt can be sent if the ordered item is out of stock?" etc.)

With our model checking approach, such specialized algorithms for checking specialized requirements (resource constraints, structural correctness etc.) can be substituted by using only one tool that can be used for verifying different kinds of properties.

# 2 Definitions

## 2.1 Workflow Specification

The Workflow Managemant Coalition defines a workflow as the computerized facilitation or automation of a business process, in whole or part[12]. A Workflow Management System (WfMS) is defined as a system that completely defines, manages and executes workflows through the execution of software whose order of execution is driven by a computer representation of the workflow logic.

In order to be processed by a WfMS, a workflow has to be specified in a formal language that can be executed by computers. This language must define the order of activation of activities and the information flow between them.

Before we give a formal definition of a workflow, we have to introduce the basic concepts:

An *activity* is a description of a piece of work that forms one logical step within a process[12]. Activities are scheduled by a WfMS. Their execution order is specified by *transitions*. In the simple case of a (sequential) transition between activities, one activity completes and the thread of control is passed to another one, which starts. To be able to define more complex business cases, we further need the control structures *AND-split*, *OR-split*, *AND-join* and *OR-join*, with the usual semantics [12].[1]

We define a *workflow specification* as follows:

**Definition 1** *A workflow specification is a 4-tuple* $(N, n_0, f, T)$*, where:*

[1] The name OR-split in [12] is a little bit misleading: XOR-split would be a better name, because one and only one transition to the next node is selected.

- *N is a set of nodes which is defined as the union $N = A \cup C$, where $A = \{a_1, \dots, a_n\}$ is a finite set of activities and $C = \{c_1, \dots, c_m\}$ is a finite set of control nodes. Each control node is either an AND-split, an OR-split, an AND join or an OR-join, which is denoted by the type function type : $C \rightarrow \{as, os, aj, oj\}$.*

- *There are two distinguished nodes: The start node $n_0 \in A$ and the end node $f \in A$.*

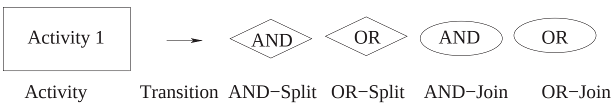
- *$T \subseteq (N \backslash \{f\}) \times (N \backslash \{n_0\})$ is a set of transitions between the nodes, where:*

  *If $(a \in A) \vee (a \in C \wedge type(a) = as) \vee (a \in C \wedge type(a) = os)$, then there exists one and only one node $b$ such that $(b, a) \in T$. (These nodes have exactly one predecessor.)*

  *If $(a \in A) \vee (a \in C \wedge type(a) = aj) \vee (a \in C \wedge type(a) = oj)$, then there exists one and only one node $b$ such that $(a, b) \in T$. (These nodes have exactly one successor.)*

The usual semantics apply: The workflow starts in its start node $n_0$. During a workflow execution, activities are executed with respect to the transitions between them. Split nodes allow us to specify concurrency and alternative and join nodes allow us to specify synchronization between incoming flows. Finally, the workflow execution stops when the final node f is reached.

To illustrate a workflow, we use a simple graphical representation with these symbols:




Split nodes have at least two outgoing transitions (arrows), while join nodes have at least two incoming transitions. Outgoing arrows from an OR-split node can be labeled with a short text describing a decision being made in the OR-split that leads to the selection of one of the outgoing arrows.

Figure 1 shows an example workflow taken from [10] and [7]. It shows a business process model for expense request payments with an option to differ between payment in US-$ or in Australian $.

## 2.2 Structural Correctness

While def. 1 defines the syntax of a workflow specification, it does not say anything about its semantics. Not every workflow specification that can be constructed using definition 1 makes sense when the semantics for splits and joins is considered. An example is shown in Fig. 2: Only one of the activities 2 and 3 will be performed after the OR-split, but the following AND-join would wait for both activities being completed. Even if the end node will be reached anyway via activity 1, it is very unlikely that this is the behavior intended by the person who has specified the workflow. For this reason it is reasonable to call such a workflow specification structurally incorrect.

We will see later in this paper that structural correctness of a workflow can be decided with our model checking approach. In fact, this is even possible without much reasoning about possible sources of structural conflicts. We just have to take into account that the result of structural incorrectness is that either a possible execution exists that does not reach the end node or there are still "uncompleted things to do" when the end node is reached. This leads us to:

**Definition 2** *A workflow specification $w = (N, n_0, f, T)$ is structurally correct if*

- *every workflow execution reaches the end node f after a finite number of transitions.*

- *when the end node is reached, all other activities that have been started before are completed and there are no remaining join nodes waiting for incoming transitions.*

Because of the limited space in this paper, we omit the formal definition of "a workflow execution" and "taking a transition", but it should be intuitively clear what those phrases stand for with respect to transitions and the semantics of split- and join-nodes[2]. Def. 2 simply requires that every sequence of nodes and transitions finally reaches the end node f after a finite number of transitions, and

[2] The only point that needs some clarification is that activities after an OR-join should *not* be activated more than once if more than one incoming flow reaches the OR-join. In this point, the semantics used in this paper differs from the one used in [10]

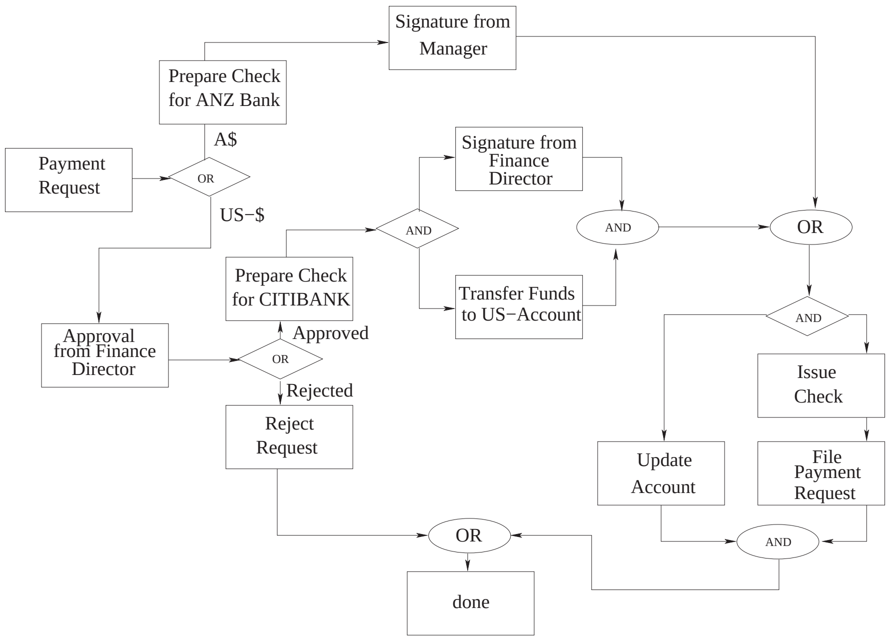



Figure 1: Sample workflow: Payment Requests

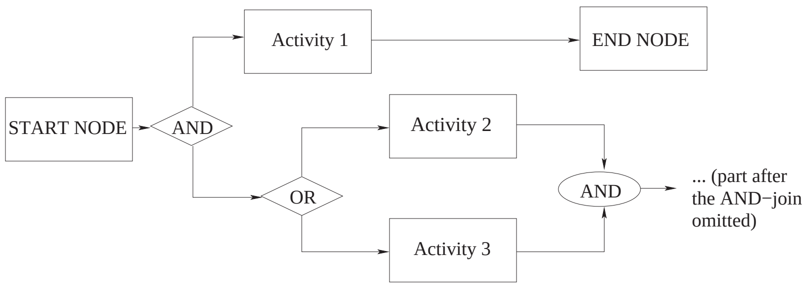



Figure 2: Semantically incorrect workflow

there are no remaining join nodes waiting for an incoming flow when the end node is reached. Infinite loops, AND-joins waiting for an incoming flow infinitely long and similar problems must not occur. Sadiq and Orlowska [13] have identified five types of possible structural errors in a workflow specification. For all five types of errors, the workflow specification will be identified as not being correct using def. 2 or it is already disallowed by the requirements for unique predecessors and successors in def. 1.

## 2.3 Timed Workflow Specifications with Ressource Constraints

Activities can require human, material or machine resources, for example a director who has to sign a bill (human resource), a vehicle to transport heavy goods (material resource) or write-access to a database (machine resource).

Often, these resources cannot be shared between different activities: When a workflow is executed, only one activity can access a resource exclusively.

This leads us to another possible source of incorrect workflow specifications: When one activity needs a resource that is occupied exclusively by another activity, the workflow is deadlocked and

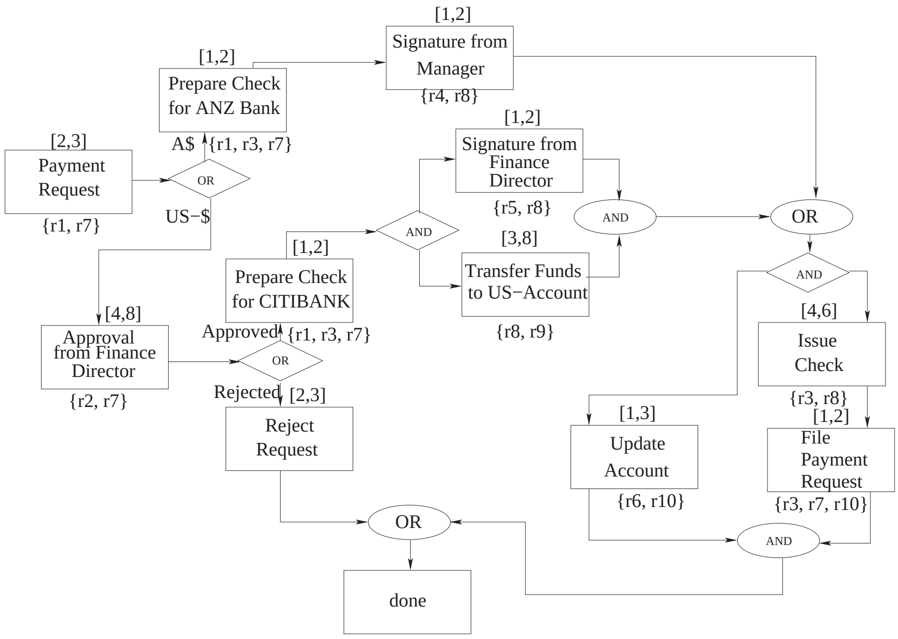



Figure 3: Workflow with information about time and resources

cannot proceed. In real life, we can formulate the previous sentence even more strictly: If the other activity occupies the required resource exclusively *until some deadline is reached*, the workflow cannot be completed in time and hence does not fulfill its purpose.

To find out whether such a situation can occur, we need to know something about the usage of resources by the activities and about the duration of the execution of activities.

**Definition 3** *Let* $R = R_1, \ldots R_n$ *be a set of resources, which cannot be shared between different activities. For each activity* $a \in A$*,* $r(a)$ *is the set of resources needed by this activity.*

**Definition 4** *The minimum time (expressed in some time unit like seconds, hours or days) that will be needed to execute an activity* $a \in A$ *is denoted by m(a), the maximum execution time will be denoted by M(a).*

We call a workflow specification with the information about minimum and maximum execution time of its activities a *timed workflow specification.* This information about timing is rather simple, but it has been shown to be sufficient for answering basic questions about deadlines and resource conflicts (for example by applying the Critical Path Method [14]). Additional elements like an interrupt construct can be added if necessary.

In Fig. 3, we add information about timing and resources to the graphical representation of the sample workflow. For each activity $a \in A$, m(a) and M(a) are given as an ordered pair [m(a),M(a)] above the activity box, the set r(a) is given below the box. Empty sets r(a) are omitted. We have taken this example from [7], with small modifications.

# 3 Model Checking of Timed Workflow Specifications

## 3.1 The Model Checker Uppaal

To verify properties of a workflow specification, we use the real-time model checking tool Uppaal [15]. We show how to translate a workflow specification into a timed automata specification that can be processed by Uppaal.

An Uppaal model is a set of timed automata, clocks, channels for handshake-synchronization, variables and additional elements. Information about the syntax for Uppaal models can be found in [15]. Here we describe some elements only.

Each Uppaal model is a set of processes (timed automata) which are depicted as states (circles) and transitions (arrows) between them.[3]

For each automaton, one state is marked as initial state (two concentric circles). A graphic representation of an Uppaal process can look like Fig. 4:

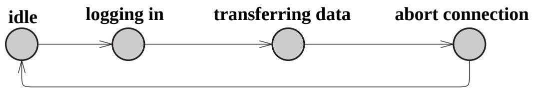



Figure 4: Simple graphic representation of a process in Uppaal

States can have the attribute "committed", depicted by the letter C inside the circle. If a state is marked as "committed, no time may pass in this state, and it must be left immediately (i.e. no interleavings with non-committed states in other automata are allowed).

When a transition is taken, clocks can be reset. (In Fig. 5 the clock named `clock1` will be reset to 0 when the transition from "idle" to "logging in" is taken), and global or local variables can be manipulated. (In Fig. 5, a variable named `active` is changed when the transition from "logging in" to "transferring data" or from "abort connection" to "idle" is taken).

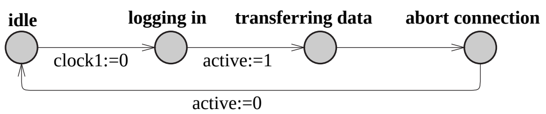



Figure 5: clocks, variables and an urgent location

Synchronization between different processes can take place using channels. When a transition is taken, a channel can be written into (written as `channelname!`). To achieve a handshake-synchronization, the corresponding reading operation (written as `channelname?`) can serve as a so-called guard of another transition which can not be taken unless reading from the channel is actually possible. If a channel is defined as urgent channel, the reading operation must be performed as soon as possible, i.e. immediately and without a delay. Fig. 6 shows a synchronization between a server process and a client process:

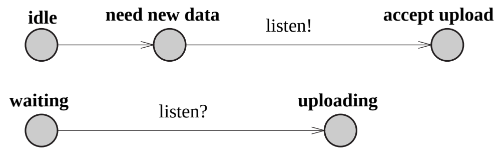



Figure 6: Using channels for handshake-synchronization

Conditions on clocks or variables can also be used as guards for transitions. This means that a transition cannot be taken until some condition (for example an equation for some variable) holds. Finally, invariants can be added to a state. We will use invariants of the type `"clock<=m"` which means that the system is not allowed to remain in this state for more than m time units. In Fig. 7, the transition will be taken when the clock named `time` is in the interval [2,4] and the value of the variable `active` fulfills the equation `active == 1`.

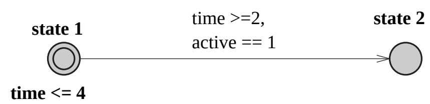



Figure 7: Guards and invariants

## 3.2 Workflow Elements in Uppaal

Using the elements introduced in the last section, we can define templates for the different kinds of nodes in a workflow specification (as defined in def. 1). Urgent channels are used to model the transitions between the nodes.

[3]Note that the meaning of an arrow in the Uppaal model is different from the meaning of an arrow in the graphical workflow representation. Also a circle in the Uppaal model does not stand for an activity like the rectangle in the graphical workflow representation does. Instead, one Uppaal process (depicted by some arrows and circles) stands for an activity.

#### 3.2.1 Start Node

The start node process does nothing else than writing into a channel `letsstart` and setting the variable `running` (which stands for the number of currently running activities) to 0:

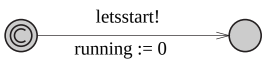



Figure 8: Start Node

#### 3.2.2 Activity Node

The UPPAAL process for an activity node waits until it becomes activated by being able to read from a channel `in_channel`. When it is activated, it sets a local clock to 0 and increments the variable `resource`. The variable `running` (the number of currently running activities) is incremented. After staying in the next state for at least mintime, but not longer than maxtime, the process comes to and end which it signalizes by writing to the channel `out_channel`. When the channel can be read by another UPPAAL process, the variable `running` (the number of currently running activities) is decremented.

#### 3.2.3 AND-Split

When activated (by the ability to read from `in_channel`), the UPPAAL process for an AND-split writes repeatedly to the channel `out_channel`, thus being able to activate more than one following node. For AND-splits with two incoming flows as used in our definition, this happens twice.

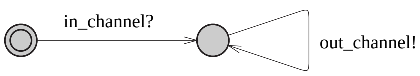



Figure 10: AND Split Node

#### 3.2.4 OR-Split

Other than the AND-split, an OR-split process writes to the channel `out_channel` only once, thus only one following node can be activated by reading from this channel.

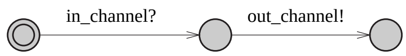



Figure 11: OR Split Node

#### 3.2.5 AND-Join

An AND-join process tries to read from two channels, `in_channel1` and `in_channel2`, and proceeds if and only if both of them are readable. (Note that it is not required that `in_channel1` is readable *before* `in_channel2`. If `in_channel2` is the first of the two channels being readable, it just "waits" and the reading operation can be performed after `in_channel1` became readable as well.)

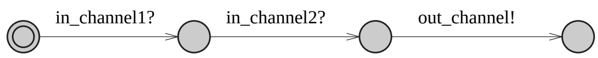



Figure 12: AND Join Node

#### 3.2.6 OR-Join

An OR-join process tries to read from two channels, `in_channel1` and `in_channel2`. It proceeds if it can read from one of them.

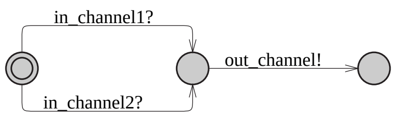



Figure 13: OR Join Node

#### 3.2.7 end-node

The UPPAAL process end stands for the end node. This process will reach the status named `finished` at the end of the model's execution.

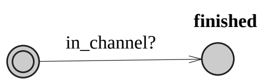



Figure 14: End Node

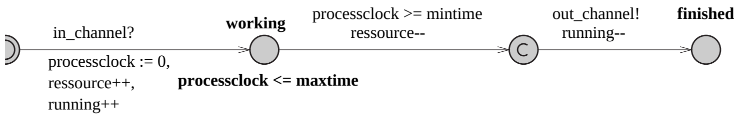



Figure 9: Activity Node

## 3.3 Translating Timed Workflow Specifications to Uppaal Models

In the previous section we have shown how the general elements of a workflow specification can be expressed as Uppaal models. To "translate" a special workflow specification into an Uppaal model, we make use of Uppaal templates. The Uppaal models of workflow nodes given in the last section are regarded as templates. This means that the names for variables, clocks and channels in the Uppaal model are placeholders (called parameters in Uppaal). To define an instance of an activity, we use this template with parameters as follows:

`Activity(processclock, mintime, maxtime, resource, in_channel, out_channel)`, where

- processclock is a placeholder for a local clock variable,
- mintime and maxtime are placeholders for numeric constants,
- ressource is the placeholder for a name of a single resource (For the sake of simplicity, we assume that each process uses at most one resource from the resource set R. By adding more placeholders, we can easily expand our model to the general case.)
- in_channel and out_channel are placeholders for urgent channels,

To instantiate the model for an actual workflow activity from the template, the placeholders are substituted by actual variables:

For example, the definition of the activity "Issue Check" from the example shown in Fig. 3 can be done by defining an instance of the template Activity as follows:

`IssueCheck := Activity(clock9,4, 6, r8, s6_channel, a10_channel);` (compare Fig.15 with Fig.9). The activity "File Payment Request" can be defined as: `FilePaymentRequest := Activity(clock11,1, 2, r10, a10_channel, a11_channel);` Note that synchronization between the both activities can take place using channel `a10_channel`, which replaces the parameter `out_channel` in the "Issue Check" activity, but `in_channel` in the "File Payment Request" activity.

Instances of control nodes can be built from the template in the same way. If a workflow specification is given according to def. 1, the translation to the Uppaal model can be done *automatically*. For each node, an instance of an Uppaal template will be generated. This means that in general, only one line of code will be added to the Uppaal model for each node in the workflow specification[4]. Split nodes with $n > 2$ outgoing transitions or join nodes with $n > 2$ incoming transitions can be transformed into a sequence of n-1 split/join nodes with two outgoing/incoming transitions.

The complete Uppaal model of our example workflow can be downloaded from ebus.informatik.uni-leipzig.de/∼laue.

## 3.4 Checking the Correctness of Timed Workflows

Having built the Uppaal model of the workflow, we can use the model checker to verify the required properties. The property specification language used in Uppaal is a subset of Timed Computational Tree Logic (TCTL) ([16].) Properties that could be checked include:

*"The end node will always be reached"* (part 1 of def. 2):

`A<> end.finished`

(The state "finished" in the process end will always be reached). This property can be checked to be true for our example workflow.

[4]plus declarations of used variables, channels and clocks and the information about the fact that the instantiated process is part of the system.

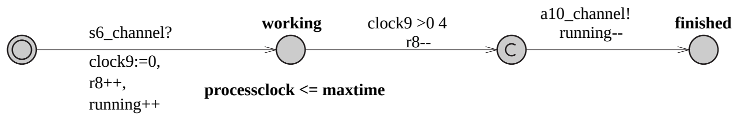



Figure 15: "Issue Check" - an instance of the Activity template

*"When the end node is reached, no activities are waiting for being finished"* (part 2 of def. 2):
`A[] end.finished imply running == 0`
This property can be checked to be true for our example workflow. (Note that `running` will not be decremented until the outgoing channel can be written into.)
*"There are no resource conflicts for resource r10"*
`A[] r10<2`
Can be checked to be true. Note that this requires reasoning about time: There are no resource conflicts, because "Update Account" is always finished when the activity "File Payment Request" starts. (Using the knowledge that "Update Account" and "File Payment Request" are the only activities that use resource r10, we will get the same verification result by checking the property `A[] UpdateAccount.working + FilePaymentRequest.working <2`. This makes use of the trick that boolean values like UpdateAccount.working are converted to numbers (0 or 1). We would not need the variables r1,...,r10, which helps to reduce the state space of the model.)
*"There are no resource conflicts for resource r8"*
`A[] r8<2`
The model checker does not only finds out that the property is violated, it also gives a counterexample: a resource conflict between the activities "Signature From Finance Director" and "Transfer Funds to US-Account"

*"If a request has been rejected, no check will be issued."*
`RejectRequest.finished --> not IssueCheck.finished`
Can be checked to be true.

*"The whole process will be completed in no more than 30 time units"*
`A<> end.finished and clock1<30`
To check this deadline constraint, we use clock1, the local clock of the first activity "Payment Request". It is started at the begin of the whole workflow. This property can be checked to be true. If we replace "30" by a smaller value, a counterexample of a process that needs 29 time units to complete will be given.

## 3.5 Remarks

### 3.5.1 Resource Pools

The approach can not only be expanded to multiple resources (if r(a) has more than one element, the model just needs more placeholders for resources used by activities), it can also be used for checking the usage of resource pools, for example a database that allows up to 10 parallel connections. We would have to check a property like `resourcecounter<=10`.

### 3.5.2 Abstraction

The timed workflow specification can be transformed automatically into an UPPAAL model which can be used as the input of the model checker. However, a complete translation of the workflow specification, preserving all its properties, does not necessarily have to be what we really want: Too many details in the model can lead to too many states the model checker has to examine.[5] Instead of translating a workflow specification while preserving all its properties, it may be a good idea to do some abstraction before by asking which parts of the system are relevant with respect to the property being checked. If we check for resource conflicts for r10 in the example workflow, information about other resources can be ignored. In fact, even only the model built from the very last part of the workflow ("Issue Check", "Update Account" and "File Payment Request") is relevant. Often, this abstraction can be done automatically.

[5] In general, models with a large number of clocks lead to a state-space explosion in timed model checking. Please note, however, that this is not the case in our model (where each activity adds a clock): When an activity is completed, its clock is not used actively in comparisons and cannot lead to new states.

## 4 Conclusion

The use of only **one** tool for verifying different kinds of properties (with or without timing information) and the simplicity of translating workflow specifications to Uppaal models are the main benefits from the results presented in our paper.

We have highlighted reasoning about structural correctness and resource constraints, but using the given approach, various other properties of workflow specifications can be checked as well. This includes the patterns identified in [3] and [17], including existence, absence, precedence and response patterns. In our further research, we will investigate such patterns, including patterns for time-related properties (see [18]). Another direction of our work will be to enable the business architects who are responsible for defining workflow specifications to specify such properties without a deeper knowledge in model checking or temporal logics.

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