An OCL Extension for Formulating Temporal Constraints

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Abstract. UML class diagrams are widely used to model the static structure of object-oriented software systems. The textual language OCL, which is part of the UML, is used for formulating constraints that can not be modeled by the diagrams. In this paper, we extend OCL with elements of linear temporal logic. With this extended OCL, which we call TOCL, we want to give software engineers a user-friendly means to specify constraints on the temporal evolution of the system structure as well as on the system behavior by stating temporal invariants and pre- and postconditions. We formally define syntax and semantics of the extended OCL.

1 Introduction

UML class diagrams are popular for modeling the static structure of object-oriented software systems. However, not all structural details can be expressed in a class diagram. Some of these details can be stated in the Object Constraint Language (OCL), a textual language for specifying additional constraints on the objects of the system. Syntax and semantics of UML diagrams are semi-formally defined in [18, 19]; OCL, which is a part of UML, is defined in [16] in the same semi-formal way. A formal semantics for UML class diagrams and OCL, which is also included in the current OCL 2.0 OMG submission [3], was given in [24, 23].

OCL is quite similar to first order predicate calculus: Boolean expressions can be built and combined by logical connectives; universal and existential quantifiers are also available. As expressions of the predicate calculus, OCL expressions used in invariants are evaluated in a single system state. In addition to such OCL invariants considering single states, OCL pre- and postconditions characterize operations by considering state transitions, i.e., state pairs.

Temporal logic and other related logics has been used successfully in the field of software development (see [20, 15, 13, 14] and [8, 26, 6, 11], among other approaches). The basic idea of (linear) temporal logic is to consider not only single states or state pairs, but to care about arbitrary state sequences. By doing so, it is possible to characterize system behavior and system evolution by specifying the allowed system state sequences as life cycles. These characterizations can be formulated as OCL constraints with temporal quantifiers as we will demonstrate with the classical steam boiler example [1].

We present an extension of OCL with important elements of a linear temporal logic. Past and future temporal operators are introduced. The motivation for our extended OCL, which we call *TOCL* (*Temporal OCL*), is as follows:

1. TOCL allows software engineers to specify constraints on the temporal evolution of a system's structure. For example, the temporal evolution of attributes and the existence of objects and links can be described with it. In contrast to other approaches, the temporal elements are smoothly integrated in the common OCL syntax, so TOCL should be easy to use for an engineer familiar with OCL. The semantics are precisely defined in a way that should be comprehensible to the intended user. The definitions are based on the formal definition of OCL presented in [24, 23] and taken up in [3]. Moreover, TOCL is an extension of OCL in the sense that all OCL constraints are also TOCL constraints with the intended semantics.
2. We describe the temporal evolution of a system by a sequence of system states. Since a system state changes due to an operation execution, it seems to be desirable to have a means to speak about these operation executions in TOCL. We allow this by introducing a new family of types – the *process types*.
3. We aim at translating UML and OCL language features to a UML/TOCL core. By such a reduction, the semantics of UML/OCL are sharpened. In this paper, we start with the reduction of pre- and postconditions to invariants in a manner that is similar to [7]. That means that pre- and postconditions are not included in the TOCL core, but of course they can still be used as syntactical sugar. Another example for a reduction is the translation of an aggregation to an association with additional TOCL constraints (see Sect. 2).
4. Several semantical aspects of elements that cannot be reduced to others can be defined precisely with TOCL, e.g. forbidden reincarnation of objects can be expressed in TOCL (see Sect. 2).

This paper is based on [27] and it is an expanded and improved version of [28]. The expansion mainly comprises the process types and the formal semantics of operation specifications.

There is already work to extend OCL with temporal logic in various directions; [21] extends OCL with operators of a linear temporal logic. However, the paper does not give a formal foundation of the extension. [5] proposes an extension of OCL with temporal operators in a similar way also without formal semantics. In [7], the object-based temporal logic BOTL is defined, which is based on the branching temporal logic CTL and a subset of OCL. But inheritance and subtyping are not considered in this approach. [10, 9] presents an OCL extension, equally based on CTL, for specification of state-oriented constraints. This extension concerns system behavior modeled by statechart diagrams; but the evolution of attributes is not considered there. [2] introduces a temporal extension of OCL also based on CTL and also regarding only dynamic diagrams. In [4], OCL is extended with temporal constructs based on the observational mu-calculus $\mathcal{O}\mu$. The authors concede that using the resulting logic $\mathcal{O}\mu$(OCL)

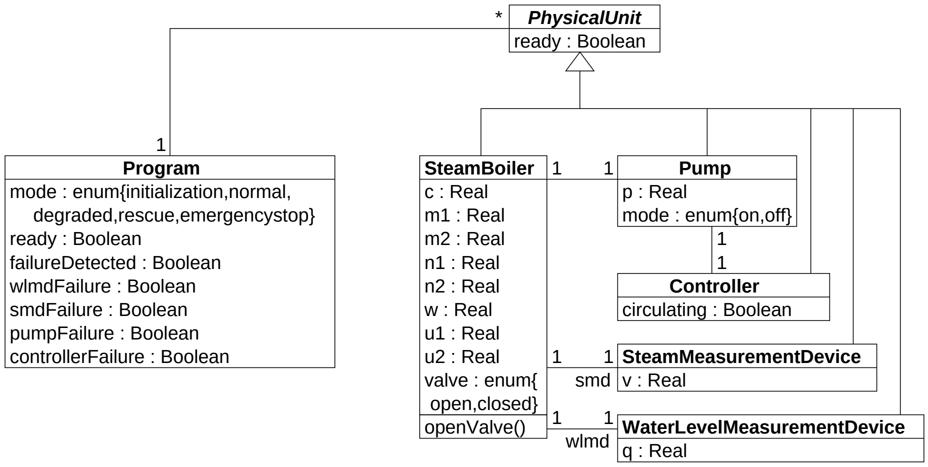

Fig. 1: Object model for the steam-boiler problem

directly requires the developer to have a profound understanding of the mathematical background, so they suggest using "templates" with user-friendly syntax which then have to be translated to $\mathcal{O}\mu$(OCL). However, due to its comprehensibility we think a direct semantics in terms of set theory is useful as well.

We emphasize that an OCL engineer can see important details about temporal OCL in this paper without consulting other work. We also think it is important to show that temporal constructs for OCL can be introduced without neccessarily using the overhead of some previously developed approach.

This paper is organized as follows. In Sect. 2, we motivate the temporal extension of OCL by giving examples. In Sect. 3, object models, system states, and state sequences are introduced as a context for TOCL. Section 4 gives a brief overview of the type system of TOCL. In the central Sect. 5, TOCL expressions and constraints are formally defined. Section 6 concludes with a summary and an outline of future work.

2 Basic Idea

To give an idea of the usefulness of a temporal OCL, we demonstrate how parts of the "Steam-boiler control specification problem" [1] can be specified using TOCL. The underlying object model is shown in Fig. 1. It is beyond the scope of this section to elaborate on all of its elements; they are explained as they are used in the following example constraints.

The first invariant states that when a program is in initialization mode, it remains in this mode until all physical units are ready or a failure of the water level measurement device has occurred. We use the temporal operator 'always-until' in this example.

```
context Program inv:
  self.mode = #initialization implies
    always self.mode = #initialization
    until (PhysicalUnit.allInstances->forAll(pu | pu.ready)
           or self.wlmdFailure)
```

The next invariant requires that the program starts in the mode 'initialization'. Here we use the well known operation 'oclIsNew', which can be used in TOCL invariants and not only in postconditions as it is the case in OCL. This invariant can also be expressed directly in the class diagram by giving an initial value to the attribute mode. Thus, the following invariant is a first example for reducing a UML feature to a TOCL invariant.

```
context Program inv:
  self.oclIsNew implies self.mode = #initialization
```

The following invariant applies the operator 'next' to specify that the mode changes from 'initialization' to 'emergencystop' if a failure of the water level measurement device is detected.

```
context Program inv:
  (self.mode = #initialization and self.wlmdFailure)
  implies next self.mode = #emergencystop
```

When the valve of a steam boiler is open, the water level measured by the water level measurement device (attribute 'q') will be lower or equal to the normal upper boundary of water level (attribute 'n2') sometime. Here, the operator 'sometime' is applied.

```
context SteamBoiler inv:
  self.valve=#open implies sometime self.wlmd.q <= n2
```

Of course, TOCL can be used in pre- and postconditions as well. The operation 'openValve()' causes the valve of the steam-boiler to be open until the water level sinks under the normal upper boundary 'n2'. The operator 'always-until' is used in the postcondition.

```
context SteamBoiler::openValve()
  post: always valve = #open until wlmd.q <= n2
```

The postcondition does not specify that the valve is closed when the water level is finally below 'n2'. Moreover, it does not say how the terminated operation assures that the valve is not opened too early. The postcondition is nothing more than a temporal property of the sequence of system states that starts with the first system state after the termination of the operation 'openValve()'.

After this practical example, we show how TOCL can be used to formally describe properties of UML. The UML semantics [19] does not mention whether "reincarnation" of instances is allowed or not. If we decide not to allow it, we can use the following invariant that applies to the UML metamodel and states that when an instance is destroyed it will not exist again sometime in the future.

```
context Instance inv forbiddenReincarnation:
  (Instance.allInstances()->includes(self) and next
   Instance.allInstances()->excludes(self))
  implies
  next (always Instance.allInstances()->excludes(self))
```

The state sequence stylized in Fig. 2 is not allowed then. A black circle denotes a state in which the object bob exists, in white states bob does not exist. The states are orderd by time from left to right.

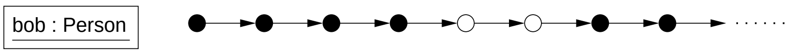

Fig. 2: Forbidden reincarnation

Another example is the sharable aggregate. The following paragraph is written in [19], page 66:

> In UML, Associations can be of three different kinds: 1) ordinary association, 2) composite aggregate, and 3) shareable aggregate. Since the aggregate construct can have several different meanings depending on the application area, UML gives a more precise meaning to two of these constructs; that is, association and composite aggregate and leaves the shareable aggregate more loosely defined in between.

One difference of shareable aggregates to ordinary associations is the forbidden instance reflexivity. This constraint can be formulated neither in OCL nor in TOCL because there is (so far) no expression computing the transitive closure. The specification leaves it to the user to specify further properties of shareable aggregations according to his own needs. In some application areas it could make sense to require a part to be connected to one of its aggregates at least once. Consider the class diagram in Fig. 3. The following invariant states that each P object has to be connected to an A1 or A2 object at some time.

```
context P inv:
  sometime (
    self.a1->notEmpty() or
    self.a2->notEmpty())
  or
  sometimePast (
    self.a1->notEmpty() or
    self.a2->notEmpty())
```

Figure 4 visualizes a state sequence that fulfills this requirement. Circles in the same vertical refer to the same state, e.g. in the second state a1 and a2 exist but p does not. The part p is connected to a1 in the fourth and fifth state.

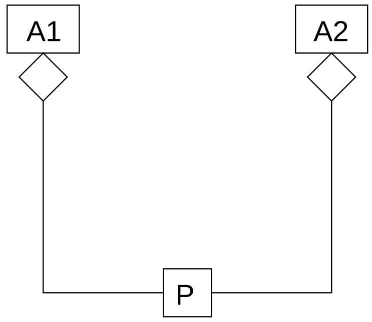

Fig. 3: Class diagram with shareable aggregation

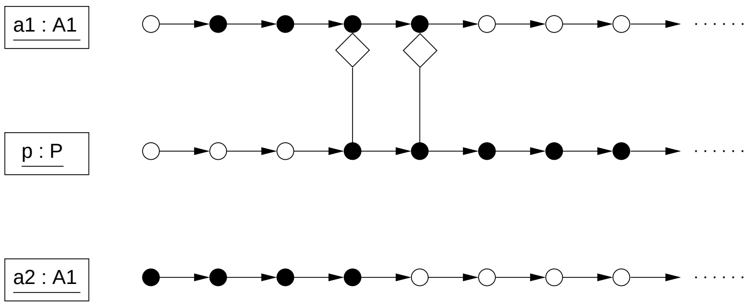

Fig. 4: p is part of a1 in two states

3 Object Models

In our context, an object model uses all those UML concepts that are essential for modeling structural aspects of a problem domain. An object model can be visualized by a UML class diagram. Instances of an object model (i.e. states of the modeled system) can be visualized by a UML object diagram. Object models are referred to by TOCL constraints and are therefore a prerequisite for the TOCL definition. We adopt the object model definition presented in [24, 23, 3] but extend it with *state sequences*.

An *object model*

$$\mathcal{M} = (\textsc{Class}, \textsc{Att}_c, \textsc{Op}_c, \textsc{Assoc}, \mathrm{associates}, \mathrm{roles}, \mathrm{multiplicities}, \prec)$$

consists of a set of classes ($\textsc{Class}$) with each class c having attributes ($\textsc{Att}_c$) and operations ($\textsc{Op}_c$) assigned to it. Associations ($\textsc{Assoc}$) connect classes with each other. The function 'associates' maps each association name to a finite list of participating classes. The function 'roles' assigns a role name to each participating class. Objects of associated classes can be connected with links. The number of links an object can be associated with is specified by the function 'multiplicities'. $\prec$ is an irreflexive partial order on the set of classes, representing a generalization hierarchy.

An object model specifies the possible states of a system. A *system state*

$$\sigma(\mathcal{M}) = (\sigma_{\text{Class}}, \sigma_{\text{Att}}, \sigma_{\text{Assoc}}, \sigma_{\text{Op}_c}, \sigma_{\text{owner}_c}, \sigma_{\text{params}_c}).$$

also called a snapshot of a running system, consists of the currently existing objects (σ_{Class}) with their current attribute values (σ_{Att}) and links (σ_{Assoc}) connecting them. Furthermore, it comprises the currently existing processes of operations of a class c (σ_{Op_c}). Actually, a "real" process in the sense of an executing operations happens between two system states. When we talk about processes, we mean instances similar to objects that exist in system states and have are closely related to the "real" processes as we will explain below. A process is mapped to its owner object by the function σ_{owner_c} and to its parameter values by the function σ_{params_c}. We write σ instead of $\sigma(\mathcal{M})$ if the model is clear from the context.

An OCL constraint is evaluated in a single system state. Since TOCL is intended for formulating constraints on the temporal evolution of a system, a single system state is not sufficient here. We therefore introduce infinite *state sequences* for a model $\mathcal{M}$, denoted as

$$\hat{\sigma}(\mathcal{M}) = \langle \sigma_0, \sigma_1, \dots \rangle.$$

The order of the states reflects a temporal relationship; that is, the system is in state σ_0 at the beginning, later in state σ_1, and so on. Again, we write $\hat{\sigma}$ instead of $\hat{\sigma}(\mathcal{M})$ if the model is clear from the context. For example, $\sigma_{0\text{Class}}(c)$ is the set of objects of class c existing in the first state of the sequence. Finite state sequences, which we do not explicitly consider, can be seen as infinite ones with one state that is followed only by empty states, i.e. states without objects.

There are several rules that have to be satisfied by a well-formed state sequence. (1) A process existing in the sequence exists only in exactly two adjacent states. The first state of these is called *prestate*, the second is called *poststate*. The operation the process belongs to is executed between pre- and poststate. Thus, our concept of process types supports only flat but not nested flow of control. (2) The owner of a process does not change. (3) The values of the input parameters do not change. (4) The value of the result parameter, if present, is undefined in the prestate. (5) There are no two processes having the same prestate and poststate. This means that a transition from state to the next is effected by exactly one operation execution.

4 TOCL Types

TOCL is a strongly typed language. We adopt the type system of OCL defined in [24, 23, 3], extending it with process types. Each type t is mapped to its domain by a function I.

The types of TOCL can by divided into several groups. The set T_B of basic types includes *Integer*, *Real*, *Boolean* and *String* with the expected domains.

Enumeration types (T_E) are user-defined; that is, the user specifies the name and a list of possible values for the type. Object types (T_C) are derived from the object model. There is an object type for each class, having the same name as the corresponding class. The domain of an object type is an infinite set of objects of the class. Process types (T_P) are also derived from the model. For each operation the user has defined as part of a class declaration there is a process type. The concrete syntax of such a type is $C :: \omega(t_1, \ldots, t_n)$ for an operation without result and $C :: \omega(t_1, \ldots, t_n) : t_{n+1}$ for an operation with result of type t_{n+1}, respectively. The domain of a process type is an infinite set of instances which we call "processes" of the operation.

Collections of values can be described by the complex types $\mathit{Set}(t)$, $\mathit{Sequence}(t)$, $\mathit{Bag}(t)$, and $\mathit{Collection}(t)$. The parameter t denotes the type of the elements of the set, sequence, or bag (multi-set), respectively. Each type has a special undefined value $\perp$ contained in its domain.

Each type has a set of associated operations. Each operation on a type t is mapped to a function by a function $I(\hat{\sigma}, i)$, i.e., the semantics of operations can depend on a state sequence and a reference index i denoting the current state. However, most operations only depend on the current state or on no state at all.

Some operations are defined on all types: a constant operation that generates the undefined value, tests for equality and inequality of two values of the same type, and a test that allows to check whether an arbitrary value is defined. Operations on the basic types, collected in a set Ω_B, include the usual arithmetic operations ($+, -, *, /$, etc.) and comparison operations ($<, >, \leq, \geq$) on *Integer* and *Real* and logical operations (and, or, xor, not) on *Boolean*. Operations on *String* include concatenation, counting of characters, etc. The set of operations on enumeration types (Ω_E) includes only those defined for all types.

Operations on object types (Ω_C) allow access to attribute values of an object in the reference state and navigation along links connecting objects. (When applied to an object not existing in the reference state, these operations result in $\perp$.) They also include user-defined operations without side effects, i.e. side effect free operations depicted in an operation slot of a class in the classdiagram. The user has to give an OCL expression with a free variable for each parameter of the operation to define its semantics.

In addition, the operations 'allInstances' and 'oclIsNew' are defined on object types. 'oclIsNew' is already present in OCL but only applicable in postconditions. In TOCL it can be applied in invariants and preconditions as well. The result of 'allInstances' is the set of objects of the given type existing in the current state. This includes instances of child classes of the corresponding class. The operation 'oclIsNew' can be used to check whether an object is new, that is, whether it exists in the current state and not in the preceding state. In the first state of a sequence, all existing objects are new.

The operations 'allInstances' and 'oclIsNew' are also defined for all process types $t \in T_P$, analogously to the object type operations with the same name. The result of 'allInstances' then is the set of processes of the given type existing in the reference state. In each state, at most two processes (of any type) can exist:

one marking a prestate and one marking a poststate. ‘oclIsNew’ checks whether a process is new. Furthermore, there are parameter operations and an owner operation on process types. Parameter operations allow access to the values of operation parameters, one of them being the result parameter (if existing). The names of these operations correspond to the names of the respective parameters. The operation returns the object the process is running on.

With t being the process type corresponding to an operation ω of a class c (i.e., $\omega \in \mathrm{OP}_c$), the semantics function I, which depends on a state sequence and a reference index, maps the operation signatures of ‘allInstances’ and ‘oclIsNew’ to functions as follows:

$$I(\hat{\sigma}, i)(\text{allInstances}_t : \rightarrow Set(t)) = \sigma_{i\,\mathrm{OP}_c}(\omega),$$
$$I(\hat{\sigma}, i)(\text{oclIsNew}_t : t \rightarrow Boolean)(\underline{m}) =$$
$$\begin{cases} \text{true} & \text{if } i > 0 \text{ and } \underline{m} \in I(\hat{\sigma}, i)(\text{allInstances}_t) \\ & \text{and } \underline{m} \notin I(\hat{\sigma}, i-1)(\text{allInstances}_t), \\ \text{true} & \text{if } i = 0 \text{ and } \underline{m} \in I(\hat{\sigma}, i)(\text{allInstances}_t), \\ \text{false} & \text{otherwise.} \end{cases}$$

Operations on complex types include constructors (mkSet, mkSequence and mkBag, respectively). For example, ‘mkset(1,2)’ results in a set containing the two integers 1 and 2. They also include operations for intersection, union, counting elements, etc.

We describe the type system of TOCL in a model signature $\Sigma_{\mathcal{M}} = (T_{\mathcal{M}}, \leq, \Omega_{\mathcal{M}})$. $T_{\mathcal{M}}$ is the union of all types for a model $\mathcal{M}$, $\Omega_{\mathcal{M}}$ is the union of associated operations, and $\leq$ is a type hierarchy. The type hierarchy is a reflexive partial order on the set of types, defining a subtype relationship. The subtype relationship between object types is derived from the class hierarchy. Process types are not ordered hierarchicaly. *Integer* is a subtype of *Real* (denoted as $Integer \leq Real$) and *oclAny* is the supertype of all other simple types. Set, sequence and bag types are subtypes of collection types. And finally, a set/sequence/bag type is a subtype of another set/sequence/bag type if the parameter type of the first is a subtype of the second.

5 TOCL Expressions and Constraints

In this section we define syntax and semantics of expressions and constraints. Expressions are build recursively upon the initial set of syntactical elements contained in a model signature. Expressions are used to construct constraints on a model. A constraint can either be an invariant or an operation specification (with pre- and postconditions).

5.1 Expressions

We now define the syntax of TOCL expressions. Rules 1–6, adopted from [24, 23], form the static expressions. The remaining rules are used to build future and past expressions. The definition of these (except for the modifiers @next and @pre) is inspired by the temporal logic defined in [25]. For each expression the set of free occurrences of variables is also defined.

Definition 1 (Syntax of expressions)
Let $\Sigma_{\mathcal{M}} = (T_{\mathcal{M}}, \leq, \Omega_{\mathcal{M}})$ be a model signature over an object model $\mathcal{M}$. Let $\mathrm{Var} = \{\mathrm{Var}_t\}_{t \in T_{\mathcal{M}}}$ be a family of variable sets where each variable set is indexed by a type t. The syntax of expressions over the signature $\Sigma_{\mathcal{M}}$ is given by a set $\mathrm{Expr} = \{\mathrm{Expr}_t\}_{t \in T_{\mathcal{M}}}$ and a function free : $\mathrm{Expr} \rightarrow \mathcal{F}(\mathrm{Var})$ that are defined as follows.[1]

1. If $v \in \mathrm{Var}_t$ then $\boldsymbol{v} \in \mathrm{Expr}_t$ and $\mathrm{free}(v) := \{v\}$.
2. If $v \in \mathrm{Var}_{t_1}, e_1 \in \mathrm{Expr}_{t_1}, e_2 \in \mathrm{Expr}_{t_2}$ then $\mathbf{let}\ \boldsymbol{v = e_1}\ \mathbf{in}\ \boldsymbol{e_2} \in \mathrm{Expr}_{t_2}$ and $\mathrm{free}(\text{let } v = e_1 \text{ in } e_2) := (\mathrm{free}(e_1) \cup \mathrm{free}(e_2)) - \{v\}$.
3. If $\omega : t_1 \times \cdots \times t_n \rightarrow t \in \Omega_{\mathcal{M}}$ and $e_i \in \mathrm{Expr}_{t_i}$ for all $i = 1, \ldots, n$ then $\boldsymbol{\omega(e_1, \ldots, e_n)} \in \mathrm{Expr}_t$ and $\mathrm{free}(\omega(e_1, \ldots, e_n)) := \mathrm{free}(e_1) \cup \cdots \cup \mathrm{free}(e_n)$.
4. If $e_1 \in \mathrm{Expr}_{Boolean}$ and $e_2, e_3 \in \mathrm{Expr}_t$ then $\mathbf{if}\ \boldsymbol{e_1}\ \mathbf{then}\ \boldsymbol{e_2}\ \mathbf{else}\ \boldsymbol{e_3}\ \mathbf{endif}$ $\in \mathrm{Expr}_t$ and $\mathrm{free}(\text{if } e_1 \text{ then } e_2 \text{ else } e_3 \text{ endif}) := \mathrm{free}(e_1) \cup \mathrm{free}(e_2) \cup \mathrm{free}(e_3)$.
5. If $e \in \mathrm{Expr}_t$ and $t' \leq t$ or $t \leq t'$ then $\boldsymbol{(e}\ \mathbf{asType}\ \boldsymbol{t')} \in \mathrm{Expr}_{t'}$, $\boldsymbol{(e}\ \mathbf{isTypeOf}\ \boldsymbol{t')} \in \mathrm{Expr}_{Boolean}$, $\boldsymbol{(e}\ \mathbf{isKindOf}\ \boldsymbol{t')} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}((e \text{ asType } t')) := \mathrm{free}(e)$, $\mathrm{free}((e \text{ isTypeOf } t')) := \mathrm{free}(e)$, $\mathrm{free}((e \text{ isKindOf } t')) := \mathrm{free}(e)$.
6. If $e_1 \in \mathrm{Expr}_{Collection(t_1)}$, $v_1 \in \mathrm{Var}_{t_1}, v_2 \in \mathrm{Var}_{t_2}$, and $e_2, e_3 \in \mathrm{Expr}_{t_2}$ then $\boldsymbol{e_1 \rightarrow}\mathbf{iterate}\boldsymbol{(v_1; v_2 = e_2 \mid e_3)} \in \mathrm{Expr}_{t_2}$ and $\mathrm{free}(e_1 \rightarrow \mathrm{iterate}(v_1; v_2 = e_2 \mid e_3)) := (\mathrm{free}(e_1) \cup \mathrm{free}(e_2) \cup \mathrm{free}(e_3)) - \{v_1, v_2\}$.
7. If $e \in \mathrm{Expr}_{Boolean}$ then $\mathbf{next}\ \boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{next } e) := \mathrm{free}(e)$.
8. If $e \in \mathrm{Expr}_{Boolean}$ then $\mathbf{always}\ \boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{always } e) := \mathrm{free}(e)$.
9. If $e \in \mathrm{Expr}_{Boolean}$ then $\mathbf{sometime}\ \boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{sometime } e) := \mathrm{free}(e)$.
10. If $e_1, e_2 \in \mathrm{Expr}_{Boolean}$ then $\mathbf{always}\ \boldsymbol{e_1}\ \mathbf{until}\ \boldsymbol{e_2} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{always } e_1 \text{ until } e_2) := \mathrm{free}(e_1) \cup \mathrm{free}(e_2)$.
11. If $e_1, e_2 \in \mathrm{Expr}_{Boolean}$ then $\mathbf{sometime}\ \boldsymbol{e_1}\ \mathbf{before}\ \boldsymbol{e_2} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{sometime } e_1 \text{ before } e_2) := \mathrm{free}(e_1) \cup \mathrm{free}(e_2)$.
12. If $\omega : t_1 \times \cdots \times t_n \rightarrow t \in \Omega_{\mathcal{M}}$ and $e_i \in \mathrm{Expr}_{t_i}$ for all $i = 1, \ldots, n$ then $\boldsymbol{\omega}\mathbf{@next}\boldsymbol{(e_1, \ldots, e_n)} \in \mathrm{Expr}_t$ and $\mathrm{free}(\omega@\mathrm{next}(e_1, \ldots, e_n)) := \mathrm{free}(e_1) \cup \cdots \cup \mathrm{free}(e_n)$.
13. If $e \in \mathrm{Expr}_{Boolean}$ then $\mathbf{previous}\ \boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{previous } e) := \mathrm{free}(e)$.
14. If $e \in \mathrm{Expr}_{Boolean}$ then $\mathbf{alwaysPast}\ \boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{alwaysPast } e) := \mathrm{free}(e)$.
15. If $e \in \mathrm{Expr}_{Boolean}$ then $\mathbf{sometimePast}\ \boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{sometimePast } e) := \mathrm{free}(e)$.
16. If $e_1, e_2 \in \mathrm{Expr}_{Boolean}$ then $\mathbf{always}\ \boldsymbol{e_1}\ \mathbf{since}\ \boldsymbol{e_2} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{always } e_1 \text{ since } e_2) := \mathrm{free}(e_1) \cup \mathrm{free}(e_2)$.

[1] $\mathcal{F}(\mathrm{Var})$ denotes the set of all finite subsets of Var.

17. If $e_1, e_2 \in \mathrm{Expr}_{Boolean}$ then **sometime e_1 since e_2** $\in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\text{sometime } e_1 \text{ since } e_2) := \mathrm{free}(e_1) \cup \mathrm{free}(e_2)$.
18. If $\omega : t_1 \times \cdots \times t_n \to t \in \Omega_{\mathcal{M}}$ and $e_i \in \mathrm{Expr}_{t_i}$ for all $i = 1, \ldots, n$ then **ω@pre$(e_1, \ldots, e_n)$** $\in \mathrm{Expr}_t$ and $\mathrm{free}(\omega@\mathrm{pre}(e_1, \ldots, e_n)) := \mathrm{free}(e_1) \cup \cdots \cup \mathrm{free}(e_n)$.

An expression of type t' is also an expression of a more general type t. For all $t' \leq t$: if $e \in \mathrm{Expr}_{t'}$ then $e \in \mathrm{Expr}_t$. □

An operation expression (rule 3) may also be written in OCL path syntax as $e_1.\omega(e_2, \ldots, e_n)$. If e_1 denotes a collection value, an arrow symbol is used instead of the period: $e_1 \to \omega(e_2, \ldots, e_n)$. Operations such as addition are denoted in infix notation.

Many important OCL constructs such as forAll, exists, select, collect, etc. can be defined in terms of an iterate expression (rule 6). See [23] for further details.

The following definition gives semantics to the TOCL expressions. Expressions are evaluated in an environment $\tau = (\hat{\sigma}, i, \beta)$ consisting of a state sequence $\hat{\sigma}$, a reference index i denoting the current state, and a variable assignment β. Concerning the first six rules, the extended environment τ is the only modification to the definition in [24, 23], where the environment contains just a state and a variable assignment.

Definition 2 (Semantics of expressions)
Let Env be the set of environments, $I(t)$ is the domain of type t, and $I(\hat{\sigma}, i)(\omega)$ the function that is the semantics of ω in a state sequence $\hat{\sigma}$ and with the current state σ_i. The semantics of a static expression $e \in \mathrm{Expr}_t$ is a function $I[\![e]\!] : \mathrm{Env} \to I(t)$ that is defined as follows.

1. $I[\![v]\!](\tau) = \beta(v)$.
2. $I[\![\text{let } v = e_1 \text{ in } e_2]\!](\tau) = I[\![e_2]\!](\hat{\sigma}, i, \beta\{v / I[\![e_1]\!](\tau)\})$.
3. $I[\![\omega(e_1, \ldots, e_n)]\!](\tau) = I(\hat{\sigma}, i)(\omega)(I[\![e_1]\!](\tau), \ldots, I[\![e_n]\!](\tau))$.
4. $I[\![\text{if } e_1 \text{ then } e_2 \text{ else } e_3 \text{ endif}]\!](\tau) = \begin{cases} I[\![e_2]\!](\tau) & \text{if } I[\![e_1]\!](\tau) = \text{true}, \\ I[\![e_3]\!](\tau) & \text{if } I[\![e_1]\!](\tau) = \text{false}, \\ \perp & \text{otherwise.} \end{cases}$
5. $I[\![(e \text{ asType } t')]\!](\tau) = \begin{cases} I[\![e]\!](\tau) & \text{if } I[\![e]\!](\tau) \in I(t'), \\ \perp & \text{otherwise.} \end{cases}$

   $I[\![(e \text{ isTypeOf } t')]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![e]\!](\tau) \in I(t') - \bigcup_{t'' < t'} I(t''), \\ \text{false} & \text{otherwise.} \end{cases}$

   $I[\![(e \text{ isKindOf } t')]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![e]\!](\tau) \in I(t'), \\ \text{false} & \text{otherwise.} \end{cases}$
6. $I[\![e_1 \to \text{iterate}(v_1; v_2 = e_2 \mid e_3)]\!](\tau) = I[\![e_1 \to \text{iterate}'(v_1 \mid e_3)]\!](\tau')$ where $\tau' = (\hat{\sigma}, i, \beta')$ and $\tau'' = (\hat{\sigma}, i, \beta'')$ are environments with modified variable

assignments

$$\beta' := \beta\{v_2/I[\![\, e_2 \,]\!](\tau)\}$$
$$\beta'' := \beta'\{v_2/I[\![\, e_3 \,]\!](\hat{\sigma}, i, \beta'\{v_1/x_1\})\}$$

and iterate$'$ is defined as:
If $e_1 \in \text{Expr}_{Sequence(t_1)}$ then $I[\![\, e_1 \rightarrow \text{iterate}'(v_1 \mid e_3) \,]\!](\tau') =$

$$\begin{cases} I[\![\, v_2 \,]\!](\tau') \\ \quad \text{if } I[\![\, e_1 \,]\!](\tau') = \langle\rangle, \\ I[\![\, \text{mkSequence}_{t_1}(x_2, \ldots, x_n) \rightarrow \text{iterate}'(v_1 \mid e_3) \,]\!](\tau'') \\ \quad \text{if } I[\![\, e_1 \,]\!](\tau') = \langle x_1, \ldots, x_n \rangle. \end{cases}$$

For $e_1 \in \text{Expr}_{Set(t_1)}$ and $e_1 \in \text{Expr}_{Bag(t_1)}$, iterate' is defined analogously.

7. $I[\![\, \text{next } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, i+1, \beta) = \text{ true}, \\ \text{false} & \text{otherwise.} \end{cases}$
8. $I[\![\, \text{always } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{ true for all } j \geq i, \\ \text{false} & \text{otherwise.} \end{cases}$
9. $I[\![\, \text{sometime } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{true for some } j \geq i, \\ \text{false} & \text{otherwise.} \end{cases}$
10. $I[\![\, \text{always } e_1 \text{ until } e_2 \,]\!](\tau) =$
$$\begin{cases} \text{true} & \text{if there is a } k \geq i \text{ with } I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true} \\ & \text{and } I[\![\, e_1 \,]\!](\hat{\sigma}, j, \beta) = \text{true for all } i \leq j < l \\ & \text{with } l = \min\{k \geq i \mid I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true}\}, \\ \text{true} & \text{if there is no } k \geq i \text{ with } I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true} \\ & \text{and } I[\![\, e_1 \,]\!](\hat{\sigma}, j, \beta) = \text{true for all } j \geq i, \\ \text{false} & \text{otherwise.} \end{cases}$$
11. $I[\![\, \text{sometime } e_1 \text{ before } e_2 \,]\!](\tau) =$
$$\begin{cases} \text{true} & \text{if there is a } k \geq i \text{ with } I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true} \\ & \text{and } I[\![\, e_1 \,]\!](\hat{\sigma}, j, \beta) = \text{true for some } i \leq j < l \\ & \text{with } l = \min\{k \geq i \mid I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true}\}, \\ \text{true} & \text{if there is no } k \geq i \text{ with } I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true} \\ & \text{and } I[\![\, e_1 \,]\!](\hat{\sigma}, j, \beta) = \text{true for some } j \geq i, \\ \text{false} & \text{otherwise.} \end{cases}$$
12. $I[\![\, \omega@\text{next}(e_1, \ldots, e_n) \,]\!](\tau) =$
$I(\hat{\sigma}, i+1)(\omega)(I[\![\, e_1 \,]\!](\tau), \ldots, I[\![\, e_n \,]\!](\tau))$.
13. $I[\![\, \text{previous } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } i = 0 \text{ or } I[\![\, e \,]\!](\hat{\sigma}, i-1, \beta) = \text{ true}, \\ \text{false} & \text{otherwise.} \end{cases}$
14. $I[\![\, \text{alwaysPast } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{ true for all } 0 \leq j < i, \\ \text{false} & \text{otherwise.} \end{cases}$
15. $I[\![\, \text{sometimePast } e \,]\!](\tau) =$
$$\begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{true for some } 0 \leq j < i, \\ \text{false} & \text{otherwise.} \end{cases}$$

16. $I[\![\, \text{always } e_1 \text{ since } e_2 \,]\!](\tau) =$
$$\begin{cases} \text{true} & \text{if } I[\![\, e_1 \,]\!](\hat{\sigma}, j, \beta) = \text{true for all } l < j \leq i \\ & \text{with } l = \max\left\{\{k \mid 0 \leq k \leq i \wedge I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true}\} \cup \{-1\}\right\}, \\ \text{false} & \text{otherwise.} \end{cases}$$
17. $I[\![\, \text{sometime } e_1 \text{ since } e_2 \,]\!](\tau) =$
$$\begin{cases} \text{true} & \text{if } I[\![\, e_1 \,]\!](\hat{\sigma}, j, \beta) = \text{true for some } l < j \leq i \\ & \text{with } l \text{ defined as in 17,} \\ \text{false} & \text{otherwise.} \end{cases}$$
18. $I[\![\, \omega @\text{pre}(e_1, \ldots, e_n) \,]\!](\tau) =$
$$\begin{cases} I(\hat{\sigma}, i-1)(\omega)(I[\![\, e_1 \,]\!](\tau), \ldots, I[\![\, e_n \,]\!](\tau)) & \text{if } i > 0, \\ \perp & \text{otherwise.} \end{cases}$$

□

An expression ‘next e’ is true if e is true “in the next state”; that is, if e is true with a reference index incremented by one. Otherwise the evaluation results in false.

An expression ‘always e’ is true if e is true in the reference state and in all future states of the sequence, otherwise false. An expression ‘sometime e’ is true if e is true in the current state or in at least one of the future states. Otherwise it is false.

‘always e_1 until e_2’ is true if e_1 is true “from now on” (including the reference state) until e_2 is true for the first time in future. The expression is also true if e_2 is never true and e_1 is true in all future states. Otherwise it is false. For an expression ‘sometime e_1 before e_2’ to be true, e_1 just has to be true in at least one future state. One of these has to be before the next future state e_2 is true in (if there is one).

The @next modifier applied to an operation has the effect of evaluating the operation in the next state.

The past expressions ‘previous e’, ‘existsPrevious e’, ‘alwaysPast e’, ‘sometimePast e’, ‘always e_1 since e_2’, ‘sometime e_1 since e_2, and the modifier @pre are defined analogously. They behave like the future expressions flipped (with respect to to the temporal ordering) across the reference state, with the difference that the sequence of past states is bounded by the first state.

Figures 5–8 show example state sequences in which given expression are true resp. false. Black circles denote states in which e_1 is true, e_2 is true in gray states. The current state is marked by an extra circle. Each line visualizes an individual state sequence, e.g., in the state sequence visualized by the first line in Fig. 5 and with the second state as the current state, the expression ‘always e_1 until e_2’ is true. In the state sequence shown beneath, the same expression is false because e_1 is false in the fifth state.

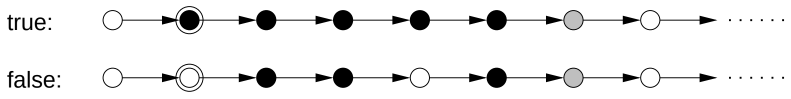

Fig. 5: always e_1 until e_2

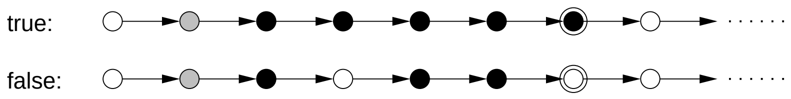

Fig. 6: always e_1 since e_2

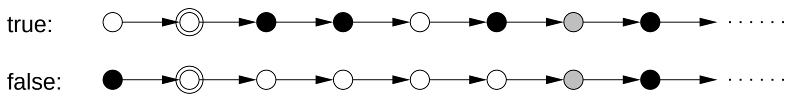

Fig. 7: sometime e_1 before e_2

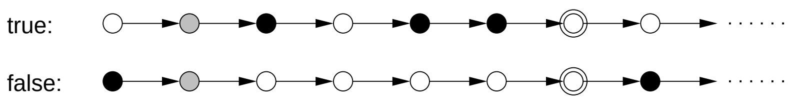

Fig. 8: sometime e_1 since e_2

5.2 Constraints

A TOCL constraint can either be an invariant or an operation specification. In this section, we formally define syntax and semantics of both of them. The set of OCL constraints is a subset of the set of TOCL constraints.

Invariants. An invariant is a condition that must be satisfied in all system states. The syntax of invariants is defined as follows.

Definition 3 (Syntax of invariants)
Let $\Sigma_\mathcal{M} = (T_\mathcal{M}, \leq, \Omega_\mathcal{M})$ be a model signature over an object model $\mathcal{M}$. Let $t_1, \ldots, t_n$ be types in $T_C \cup T_P, v_i$ variables in Var_{t_i} for all $1 \leq i \leq n$ and e a boolean expression in $\text{Expr}_{Boolean}$ with $\text{free}(e) = \{v_1, \ldots, v_n\}$. Then an invariant is of the following form:

`context` $v_1 : t_1, \ldots, v_n : t_n$ **`inv:`** e

$\square$

The variables declared in the context can have object or process type. An example of an invariant on a process type is the invariant an operation specification is reduced to (see Def. 6). Other types such as *Integer* are not allowed because of the infinity of their domains.

The context specification can be abbreviated in some cases. If only one variable is to be declared then it does not have to be named explicitly, only the type must be provided. In this case the variable 'self' of the given type is declared implicitly. If there are no free variables in e then the context can be omitted. If several variables are of the same type then the type has to be specified only once. We proceed with the semantics of invariants.

Definition 4 (Semantics of invariants)
An invariant $\phi = \textbf{context } v_1 : t_1, \ldots, v_n : t_n \textbf{ inv}\text{: } e$ is *valid in a state sequence* $\hat{\sigma}$, denoted as $\hat{\sigma} \models \phi$, if $I[\![e']\!](\hat{\sigma}, 0, \beta) = \text{true}$ with e' being the following expression:

```
always(
  t1.allInstances->forAll(v1:t1 |
     ...
     tn.allInstances->forAll(vn:tn |
       e
     )
     ...
  )
)
```

An invariant that is not valid is denoted as $\hat{\sigma} \not\models \phi$. □

The expression e is extended to an expression e' that prepends an 'always' operator and quantifies the declared variables over the set of objects/processes of the respective type existing in the respective state. The fact that an invariant is a condition that must *always* be satisfied is therefore made explicit here. Every OCL invariant is also a TOCL invariant with semantics as expected.

The assignment β is irrelevant for the result since there are no free variables in e'.

Pre- and Postconditions. Pre- and postconditions are part of operation specifications. They are used to specify conditions to be satisfied before and after the execution of a user-defined operation, respectively. The syntax of operation specifications is defined as follows.

Definition 5 (Syntax of operation specifications)
For an operation $\omega : t_c \times t_1 \times \cdots \times t_n \to t \in \Omega_C$ with $\text{params}_c(\omega) = \langle p_1, \ldots, p_n \rangle$ an operation specification is of the following form:

```
context C :: ω(p1 : t1, ..., pn : tn) : t
  pre: e_pre
  post: e_post
```

e_{pre} (the *precondition*) and e_{post} (the *postcondition*) are boolean expressions that may contain $p_1, \ldots, p_n$ 'result', and 'self' as free variables. $p_i \in \mathrm{Var}_{t_i}$ for all $1 \leq i \leq n$, result $\in \mathrm{Var}_t$, and self $\in \mathrm{Var}_{t_c}$.

Accordingly, for an operation without result parameter, ": t" is omitted and there is no variable 'result'.

If the condition (and the keyword in front of it) is omitted, then a condition with value true is specified implicitly. □

We now define the semantics of operation specifications. In our context, operation specifications turn out to be special invariants, whose semantics are already defined.

Definition 6 (Semantics of operation specifications)
An operation specification $\psi =$

context $C :: \omega(p_1 : t_1, \ldots, p_n : t_n) : t$
  pre: e_{pre}
  post: e_{post}

is *valid in a state sequence* $\hat{\sigma}$, denoted as $\hat{\sigma} \models \psi$, if $\hat{\sigma} \models \phi$ with ϕ being the following invariant:

context `m:`$C :: \omega(t_1, \ldots, t_n) : t$ **inv:**
  `(m.oclIsNew and` translate(e_{pre})`)`
  `implies`
  `next` translate(e_{post})`)`

The function 'translate' modifies expressions in the following manner:

- All occurrences of the variables $p_i \in \mathrm{params}_c(\omega)$ are replaced by 'm.p_i()'.
- All occurrences of the variable 'self' are replaced by 'm.owner()'.
- All occurrences of the variable 'result' are replaced by 'm.result()'.

The semantics of an operation specification for an operation without result parameter is defined accordingly. □

The function translate replaces the free variables by the appropriate operation calls on the respective process.

For an operation specification to be valid in a state sequence, the postcondition must be satisfied in the poststate of all processes of the given operation if the precondition is satisfied in the corresponding prestate.

Figure 9 shows a state sequence that refers to the steam boiler example in Sect. 2. A process of the operation 'openValve()' of class SteamBoiler exists in the second and third state, thus the second state is the pre- and the third state is the poststate. The postcondition specified in Sect. 2 requires that the valve of the owner of the process (i.e. the steam boiler 'openValve()' is applied to) is open until the water level measurement device measures a water level lower or equal to 'n2'. The shown state sequence fulfills this requirement, so the operation specification is valid in this state sequence.

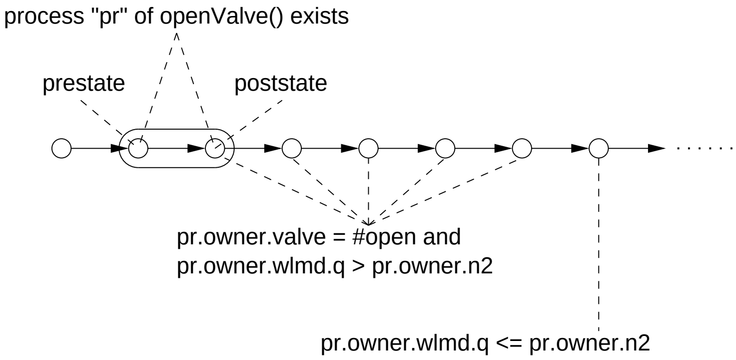

Fig. 9: Processes in a state sequence

The semantics of pre- and postconditions has been defined in [7] in a similar way by formulating an equivalent invariant with BOTL, a branched temporal logic based on CTL and OCL.

6 Summary and Conclusions

In this paper we have formally defined TOCL, an extension of OCL with elements of a linear temporal logic. We have started with a description of object models, modeling the static structure of a system. System states have been introduced as snapshots of a running system. Multiple states, which are ordered in time, form state sequences that constitute part of the environment for evaluating TOCL expressions.

We have proceeded with an outline of the TOCL type system, where we have added process types to the common OCL types. The domain of process types contains processes, tagging the state they exist in to be either a pre- or a poststate of an operation execution.

In the central part of the paper, TOCL expressions and constraints have been defined. Future and past temporal operators have been introduced to combine boolean expressions to new ones. Expressions have been used to form constraints, i.e., invariants and operation specifications (with pre- and postconditions). The semantics of invariants has been formally defined, and operation specifications turned out to be a special kind of invariants, so their semantics could have been reduced to that of invariants.

There are some issues that are topics of further research. Our decision to forbid parallelism of processes for reasons of simplicity restricts the modeler quite a lot. At least it could be allowed for two processes not conflicting with each other to run at the same time. It is, however, a complex task to characterize whether two processes do not conflict, but sufficient conditions could be found.

Up to now, our concept of process types supports only flat flow of control. It has to be extended to take account for nested operation calls.

Furthermore, it could be examined to which extent TOCL is capable of describing properties of the various UML diagram types. We aim at translating parts of them (especially parts of certain statechart diagrams) to a TOCL core.

Finally, since OCL is already supported by tools like the USE tool [22] or the OCL Toolset [12], it could also be thought of a tool supporting TOCL or maybe of an add-on to an existing tool. But we currently have no plans in this direction.

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