Consistency of UML Class and Statechart Diagrams with State Invariants

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Abstract: We present an approach and a tool to analyze the consistency of UML class and statechart diagrams containing state invariants automatically. UML class diagrams describe the structure of a system as a collection of classes while UML statechart diagrams describe its behavior. State invariants relate the active state configuration of a statechart with object instances described in a class diagram. We consider a UML statechart inconsistent if it contains unsatisfiable state invariants, that is, there are no object instances that can make a given invariant evaluate to true. To detect such inconsistencies, we translate a UML model containing class and statechart diagrams into the Web Ontology Language (OWL 2), and then use OWL 2 reasoning tools to infer the consistency and satisfiability of the translated diagrams. The approach is supported by an automatic translation tool and existing OWL 2 reasoners. We demonstrate our approach with an example design and evaluate its performance using large UML models.

1 INTRODUCTION

The Unified Modeling Language (UML) is a widely used modeling notation for documenting the design of software intensive systems (OMG, 2011). A UML model usually comprises a number of diagrams providing different views of a system. These diagrams allow us to decompose the design of a large system into smaller and more manageable views. However, representing a system as a collection of diagrams raises the issue of possible design inconsistencies. In this article we address the problem of the consistency of UML class and statechart diagrams with state invariants.

A class diagram describes the structure of a system in the form of classes, their associations with each other, the attributes of each class and operations that can be invoked on them. On the other hand, a statechart diagram provides the behavioral interface of a class. It defines all possible sequences of method invocations, the conditions under which methods can be invoked and their expected results.

Each state in a statechart diagram represents a certain condition that is true when the state is active. The condition can be implicit in the design, or defined explicitly in the form of a state invariant. A state invariant is a boolean expression that is true when a given state is active and false otherwise. State invariants are defined using the attributes and associations described in the class diagram and expressed using the Object Constraint Language (OCL) (OMG, 2006).

Given a number of UML class and statechart diagrams, it is possible to specify unsatisfiable state invariants that describe states that can never be active or operations that cannot be implemented according to the well-formedness rules specified in the UML superstructure specification (OMG, 2011). An unsatisfiable state invariant is considered inconsistent with respect to a class diagram since there are no object instances that can make an unsatisfiable invariant evaluate to true.

The inconsistent state invariants are design errors and, in order to reduce development costs and time, they must be detected and corrected as early in the software development process as possible. The approach we propose to detect such inconsistencies is based on the use of the automatic reasoning tools developed initially in the context of the semantic web. We first translate the class and statechart diagrams with state invariants in a UML model to the Web Ontology Language version 2 for Description Logic (OWL 2 DL) (W3C, 2009b), and then use an OWL 2 DL reasoning tool (Sirin et al., 2007; Shearer et al., 2008; Tsarkov and Horrocks, 2006) to determine the consistency of the UML design.

The approach presented here is limited to a frag-

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ment of the OCL language, but on the other hand is decidable and fully automatic. The designer does not need to know the details of the translation or the reasoning performed by the underlying tools. Also, current reasoning tools and desktop computers can process relatively large UML models in few seconds. Therefore we consider that this approach has the potential to be integrated with existing and future UML tools and provide consistency analysis services that go beyond what is being offered in current tools that only use basic syntactic analysis and well-formed rules.

This paper is organized as follows. In Section 2, we present an overview of our approach with the help of a running example and discuss the related work. In Section 3, we discuss the problem and the proposed solution for determining the consistency of a UML model containing class and statechart diagrams. In Section 4, we present the structure and the translations of class diagrams, statechart diagrams and state invariants into OWL 2 DL. In Section 5, we discuss about the implementation of the UML to OWL 2 translations in the form of a translation tool and the consistency analysis by using OWL 2 reasoners. Finally, in Section 6, we conclude the paper.

2 CONSISTENCY OF CLASS AND STATECHART DIAGRAM

In this section we present an overview of our approach that we demonstrate with a running example and discuss previous work related to the consistency of UML diagrams.

Our example system is a Content Management System. In this system, authors post new articles to be published after being reviewed by a reviewer. A reviewer can accept, reject or advise a revision of the paper. Only an accepted article can be published. An article can be withdrawn if it is under review. However, a published article cannot be withdrawn. The structure of this system is described as a UML class diagram (Figure 1), while its behavior is described using a UML statechart diagram (Figure 2).

A statechart diagram defines behavior of a class in terms of states that an instance of a class takes during its lifecycle and the transitions between them. Each transition from a source to a target state is triggered by a function call.

The statechart diagram shown in Figure 2 defines the behavioral view of the class *Article* of the class diagram shown in Figure 1 in term of states. It consists of one composite state ArticleReview and two simple states *Publish* and *ArticleWithdraw*. The *ArticleReview* composite state consists of four simple states namely, *WaitingforReview*, *Revisioning*, *ArticleRejected* and *Accept*. When the *submit*() method is called on an object of the class *Article*, the statechart diagram is initiated and the object enters into the state *WaitingforReview* a substate of *ArticleReview*. The method calls to *accept*(), *reject*() and *revise*() take the object to the *Accept*, *ArticleRejected* and *Revisioning* state respectively. When the author of the article is revisioning the article, the object of the class *Article* is in the *Revisioning* state. When the author revises the article, he invokes the *Revisioned*() method of the *Article* class and the object again comes into the *WaitingforReview* state. The *publish*() method can be invoked from the *Accept* state and the object switched to the *Publish* state. An article can be withdrawn by invoking the method *withdraw*() whenever the state *ArticleReview* is active, but the *withdraw*() method cannot be invoked if the object of the class *Article* is in the *Publish* state.

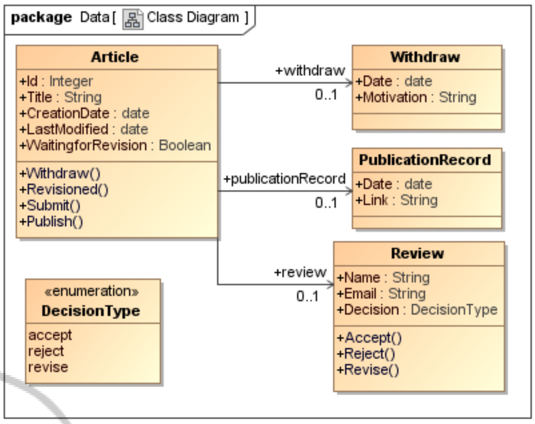


Figure 1: The static view of Content Management System.

Each state in a statechart is annotated with a state invariant. The state invariant is a boolean expression that links classes of a class diagram to the states of a statechart diagram. We say that an object of a class is in a certain state if the state invariant of that state is true. We express the state invariant of each state by using OCL and annotate the behavioral diagram of our example with state invariants in Figure 2. The details about the OCL constructs used in our approach will be discussed in Section 4.4.

We consider the state invariants which let the statechart diagram behave against the UML superstructure specifications for statechart diagrams (OMG, 2011) as inconsistent state invariants, and may cause whole system become unsatisfiable or inconsistent. The examples of inconsistent state invariants are as follows:

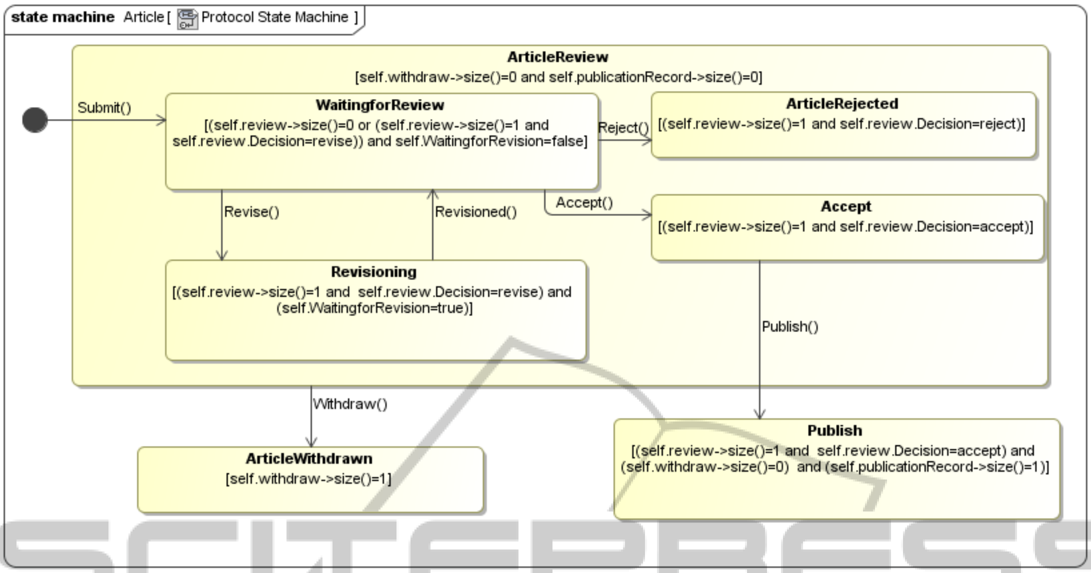


Figure 2: The behavioral view of the class *Article* of the class diagram shown in Figure 1.

Inconsistent State Invariant Example 1. According to the UML superstructure specification, invariants of non-orthogonal states must be mutually exclusive ((OMG, 2011), p.564), for example in the statechart diagram shown in Figure 2, the article cannot be in the state of *ArticleRejected* if at the same time this article is in the state of *Accept*. If we introduce an error by changing the invariant value of the state *ArticleRejected* to `self.review->size()=1 and self.review.Decision=accept`, means that an article can be rejected and accepted at the same time. The introduced error allows an object of the class *Article* to belong to two non-orthogonal states i.e. *Accept* and *ArticleRejected*, which is the violation of the UML superstructure specification of the statechart diagram, and as a consequence the invariant of states *ActicleRejected* and *Accept* becomes inconsistent.

Inconsistent State Invariant Example 2. According to the UML superstructure specification, whenever a state is active, all its superstates are active ((OMG, 2011), p.565), means all invariants of an active state and its superstates directly or transitively are true. For example, in a statechart diagram see Figure 2, if the state *Accept* is active then its superstate *ArticleReview* should be also active. If we introduce an error by adding the condition `self.withdraw->size()=1` in the invariant of the state *Accept*, means that a withdrawn article can also be accepted. The introduced error causes the contradiction between the invariants of the state *Accept* and its superstate *ArticleReview*, and violates the UML superstructure specification of the statechart diagram, and consequently makes the invariant of the states *Accept*, *ArticleReview* and *ArticleWithdrawn* inconsistent.

In the next section we discuss how we can carry out the analysis of these kind of models using OWL 2 reasoning tools.

2.1 Previous Work

The consistency analysis of UML class diagrams and statechart diagrams has been studied by a number of researchers in the recent past, but often the analysis has focused on different properties of a design. The approach by Yeung et al. (Yeung, 2004) analyzes the behavior of statecharts to find deadlocks, by translating class diagrams into the B-Method and statechart diagrams into CSP. This approach is not focused on the consistency of state invariants, the translation is done manually and there is no discussion about the verification method whether it is manual or automatic.

The approach by Rasch et al. (Rasch and Wehrheim, 2003), uses Object-Z for the formalization of class models and CSP for statechart diagrams, this approach analyzes method invocations against the class description and finds deadlocks by running the class and statechart diagram formalization in FDR. This approach is not focused on the analysis of the consistency of state invariants. Furthermore, the approach by Lam et al. (Lam and Padget, 2005) analyzes the consistency of statechart diagrams and class diagrams by using the π-calculus. The translation of UML diagrams to π-calculus is done manually and the consistency is analyzed by running the π-calculus script on the Workbench.

Moreover, the approach by Emil Sekerinski (Sekerinski, 2008) focus on the verification of statecharts. In this approach, the events are manually translated into generalized program statements, and these statements appeared as the body of a transition. The execution of the program statements is based on the assumption that the body of the transition can read or write the values of the class variables.

The use of ontology languages and description logic in the context of model validation has been proposed in the past by different authors (Van Der Straeten, 2005; Wang et al., 2006; Berardi et al., 2005; Balaban and Maraee, 2008). However, to our knowledge, none of them has addressed the reasoning of the satisfiability of state invariants using OWL 2 DL. These works focus on the problem of class diagrams satisfiability, i.e., a class diagram can generate consistent object diagrams or not. Moreover, the approach by Moaz et al. (Maoz et al., 2011), analyzes the consistency of class and object diagrams by using Alloy. This is a fully automatic approach, in this approach the class and object diagrams are first translated into a parameterized Alloy module, and then the consistency analysis is done by analyzing the translated Alloy module by using the Alloy Analyzer. This approach do not yet supports statecharts and OCL constraints. Furthermore, the TWOUSE approach (Walter et al., 2012) is focused on two areas, first is the Ontology Development Modeling (ODM), and the second is the translation and validation of Domain Specific Languages (DSL) by using OWL 2. This approach proposes same methodology for the validation of DSLs as presented in this article. However, their work on validation is limited to the validation of DSLs, and has not yet offered the validation of statechart diagrams with or without state invariants.

Furthermore, Bogumila et al. (Hnatkowska et al., 2001), analyze the consistency of the statechart diagram of a class by writing OCL rules manually, and then execute the OCL rules by using the OCL compiler. This approach is limited to analyzing consistency of statechart diagrams against the class description and not using state invariants. In OCL, the model validation rules must be defined explicitly based on the syntax of the UML models. In our approach, model validation is defined in the semantic interpretation of the OCL and UML models. The difference is that while OCL must define a large number of well-formed rules for different variations and combinations of model elements, a logic approach requires a smaller number of axioms that are often simpler.

To our knowledge, none of the above mention work proposes an automatic translation and consistency checking approach for UML class and statechart diagrams with state invariants described in OCL.

3 CONSISTENCY ANALYSIS

In this section we define the problem of determining the consistency of UML models containing class and statechart diagrams as follows. Our view of model consistency is inspired by the work of Broy et al. (Broy et al., 2009). This work considers the semantics of a UML diagram as their denotation in terms of a so-called system model and defines a set of diagrams as consistent when the intersection of their semantic interpretation is nonempty.

In our work, we assume that there is a nonempty set Δ called the object domain containing all the possible objects in our domain. We propose that a UML model depicting a number of class and statechart diagrams is interpreted as a number of subsets of Δ representing each class and each state in the model and as a number of conditions that need to be satisfied by these sets.

A UML class is represented a set C, such $C \subseteq \Delta$. An object o belongs to a UML class C iff $o \in C$. We also represent each state S in a statechart as a subset of our domain $S \subseteq \Delta$. In this interpretation, the state set S represents all the objects in the domain that have such state active, that is, object o is in UML state S iff $o \in S$.

Other elements that can appear in a UML model such as generalization of classes, association of classes, state hierarchy and state invariants are interpreted as additional conditions over the sets representing classes and states. For example class specialization is interpreted as a condition stating that the set representing a subclass is a subset of the set representing its superclass. These conditions are described in detail in the next section.

In this interpretation, the problem of a UML model consistency is then reduced to the problem of satisfiability of the conjunction of all the conditions derived from the model. If such conditions cannot be satisfied, then a UML model will describe one or more UML classes that cannot be instantiated into objects or objects that cannot ever enter a UML state in a statechart. This can be considered a design error, except in the rare occasion that a designer is purposely describing a system that cannot be realized. To analyze the UML models and discover possible inconsistencies we will use the services of an OWL 2 reasoning tool, as described in the rest of this section.

3.1 Description Logic and OWL 2

The Description Logic used in our approach is classified as $\mathcal{SROIQ}$ (Horrocks et al., 2006). Description Logic is made up of concepts, denoted here by C, D, and roles, denoted here by R, Q. A concept or role can be named, also called atomic, or it can be composed from other concepts and roles.

An interpretation I consists of a non-empty set Δ^I and an interpretation function which assigns a set $C^I \subseteq \Delta^I$ to every named concept C and a binary relation $R^I \subseteq \Delta^I \times \Delta^I$ to every named role R.

The constructors of Description Logic are as follows:

Everything	$\top^I = \Delta^I$
Nothing	$\bot^I = \emptyset$
Complement	$(\neg C)^I = \Delta^I \backslash C^I$
Inverse	$(R^-)^I = \{(y,x) \mid (x,y) \in R^I\}$
Intersection	$(C \sqcap D)^I = C^I \cap D^I$
Union	$(C \sqcup D)^I = C^I \cup D^I$
Restriction	
Universal	$(\forall R.C)^I = \{x \mid \forall y.(x,y) \in R^I \rightarrow y \in C^I\}$
Existential	$(\exists R.C)^I = \{x \mid \exists y.(x,y) \in R^I \wedge y \in C^I\}$
Cardinality	$(\geq nR)^I = \{x \mid \#\{y \mid (x,y) \in R^I\} \geq n\}$
	$(\leq nR)^I = \{x \mid \#\{y \mid (x,y) \in R^I\} \leq n\}$

where $\#X$ is the cardinality of X. The axioms in DL can be either inclusions $C \sqsubseteq D$, $C \sqsubseteq D$ or equalities $C \equiv D$, $R \equiv Q$.

An interpretation satisfies an inclusion $C \sqsubseteq D$ if $C^I \subseteq D^I$ and an inclusion $R \sqsubseteq Q$ if $R^I \subseteq Q^I$. An interpretation satisfies an equality $C \equiv D$ if $C^I = D^I$ and an equality $R \equiv Q$ if $R^I = Q^I$. I satisfies a set of axioms if it satisfies each axiom individually – I is then said to be a model of the set of axioms. Given a set of axioms $\mathcal{K}$, a named concept C is said to be satisfiable if there exists at least one model I of $\mathcal{K}$ in which $C^I \neq \emptyset$. A set of axioms is said to be satisfiable if all of the named concepts that appear in the set are satisfiable. If a set of axioms $\mathcal{K}$ is satisfiable, we say that an axiom ϕ is satisfiable with respect to $\mathcal{K}$ if $\mathcal{K} \cup \{\phi\}$ is satisfiable. Similarly, we say that ϕ is unsatisfiable (w.r.t. $\mathcal{K}$) if $\mathcal{K} \cup \{\phi\}$ is unsatisfiable.

The decidability of $\mathcal{SROIQ}$ is demonstrated by Horrocks et al. (Horrocks et al., 2006).

3.2 OWL 2 Functional Syntax

For practical reasons, we use the OWL 2 functional syntax (OWL2fs) (W3C, 2009b) as the language used as an input for the reasoners and in the text of this article. The interpretation of the main OWL 2 expressions used in this article is presented in the following table. A complete description of the OWL 2 semantics, including support for data types can be found in (W3C, 2009a).

`SubClassOf(C D)`	$C \sqsubseteq D$
`EquivalentClasses(C D)`	$C \equiv D$
`DisjointClasses(C D)`	$C \sqcap D = \emptyset$
`ObjectPropertyDomain(R C)`	$\forall R^{-1}.C$
`ObjectPropertyRange(R C)`	$\forall R.C$
`ObjectMinCardinality( n R)`	$\geq nR$
`ObjectMaxCardinality( n R)`	$\leq nR$
`ObjectExactCardinality(n R)`	$(\geq nR) \sqcap (\leq nR)$

3.3 Reasoning

In order to determine the satisfiability of the concepts represented in a UML model, we propose to represent the UML model using a Description Logic, and analyze the satisfiability of the concepts using automated reasoning tools. We have chosen OWL 2 DL to represent our UML models since we consider it is well supported and adopted, and there exist several OWL 2 reasoners (Sirin et al., 2007; Shearer et al., 2008; Tsarkov and Horrocks, 2006) for analyzing concept satisfiability. A number of UML class diagrams, statechart diagrams and state invariants are taken as an input. All the inputs are translated to OWL 2 DL, and then analyzed by a reasoner. The reasoner provides a report of unsatisfiable and satisfiable concepts. Unsatisfiable concepts will reveal UML classes that cannot be instantiated or UML states that cannot be entered.

In the next section, we discuss and translate the structure of UML models with state invariants, and the UML superstructure specification conditions over the sets representing classes and states into OWL 2 DL.

4 FROM CLASS AND STATECHART DIAGRAMS TO OWL 2 DL

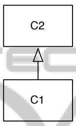
4.1 From Class Diagram to OWL 2 DL

According to the UML superstructure specification, a UML class diagram is a set of classes and their relationships in form of associations and generalizations ((OMG, 2011), p.144). In order to analyze the consistency of UML class diagrams, we need to first translate all classes and their associations into OWL 2 ontology, and then validate the OWL 2 ontology using an OWL 2 reasoner. In this section we only present the translation of those class diagram concepts which are required for the validation of statechart diagrams with state invariants such as: class, association, multiplicity, attributes and enumeration. All OWL 2 DL translations we discuss in this section are based on the Description Logic interpretation of UML concepts given in (Van Der Straeten, 2005; Wang et al., 2006; Maoz et al., 2011; Berardi et al., 2005; Balaban and Maraee, 2008; Walter et al., 2012).

4.1.1 Class

A class in a class diagram represents a collection of objects which share the same features, constraints and definition. Each class in a class diagram is treated as a *class* in OWL 2. A UML class C is translated in OWL 2 as `Declaration(Class(C))`.

4.1.2 Objects Belong to a Class also Belong to its Superclass



Class specialization is reduced to the concept inclusion. We represent the fact that a UML class C1 is a specialization of UML class C2 with the condition $C_1 \sqsubseteq C_2$. In this case we say that C2 is a superclass of C1. If C2 is a superclass of C1 we say that they are in a specialization relation. The specialization relation $C_1 \sqsubseteq C_2$ is translated in OWL 2 as `SubClassOf( C1 C2 )`.

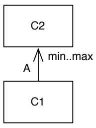
4.1.3 If an Object Belongs to Multiple Classes, they are Related by Specialization

We assume that an object cannot belong to two different classes, except when these two classes are in a specialization relation. In our semantic interpretation of a UML class diagram, it is important to denote the fact that two classes are not in a specialization relation.

We represent the fact that UML class C1 and UML class C2 are not in a specialization relation with the condition $C_1 \sqcap C_2 = \perp$. With this condition, an object cannot belong to these two classes simultaneously. Due to the open-world assumption used in Description Logic, we need to explicitly state this fact in OWL 2 as `DisjointClasses( C1 C2 )`.

4.1.4 Association

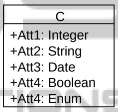
We represent a UML directed binary association A from class C1 to C2 as a relation $A : C_1 x C_2$. An association of a UML class in a class diagram is annotated with a positive number; this number indicates the multiplicity of an association. Association multiplicity describes a number of allowable objects of a range class to link with the object of a domain class. The multiplicity of an association defines additional conditions over this relation $\#\{y|(x,y) \in A\} \geq min$, $\#\{y|(x,y) \in A\} \leq max$.



A UML association A from UML class $C1$ to $C2$ and have a multiplicity (min, max) is represented in OWL 2 as:

```
Declaration(ObjectProperty(A))
ObjectPropertyDomain( A C1 )
ObjectPropertyRange( A C2 )
SubClassOf( C1
    ObjectMinCardinality( min A ) )
SubClassOf( C1
    ObjectMaxCardinality( max A ) )
```

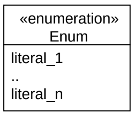
4.1.5 Attributes



Attributes containing data such as integer or boolean are also represented as relations. In this case the range of the relation A belongs to the set D represents the datatype $\forall x, y : (x,y) \in A \implies y \in D$. Also, attributes usually have a multiplicity restriction to one value. The attributes of a UML class in a class diagram are translated in OWL 2 as a *DataProperty*. In OWL 2, the data property use datatype in its range. The datatype can be xsd:boolean, xsd:string, xsd:int and other datatypes see ((W3C, 2009b), Table 3). We map attributes that use basic types by declaring a data property with the attribute's name. Also, an attribute is a required component of its class. Consequently, the data properties describing attributes have an exact cardinality of one. The attribute *Att* of the UML class *C* having any of the above mentioned *DataType* is translated in OWL 2 as:

```
Declaration(DataProperty( Att ))
SubClassOf(C DataExactCardinality(1 Att ))
DataPropertyDomain( Att C )
DataPropertyRange( Att DataType )
```

4.1.6 Enumeration



Enumeration is a kind of the datatype, whose instances are a user-defined enumeration literals ((OMG, 2011), p.67). The enumeration *Enum* is declared by using a `DatatypeDefinition` axiom in OWL 2 DL. The class attribute *Att* having a datatype *Enum*, means $\forall x, y : (x,y) \in Att \implies y \in Enum$ where *Enum* is a set of enumeration literals $\{(literal_1), \ldots, (literal_n)\}$ is represented in OWL 2 as:

```
DataPropertyRange(Att DataOneOf(
             "literal1"^^datatype ..))
```

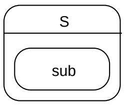
4.2 From Statechart Diagrams to OWL 2 DL

A statechart diagram provides the behavioral interface of a class and defines the sequence of method invocations, the conditions under which they can be invoked and their expected results. In order to analyze the satisfiability of state invariants in a statechart diagram, we need to translate the states and their invariants into OWL 2 DL. The translation of the state and the state invariant includes the reference of the class and its attributes. Therefore, we translate a statechart diagram in the same ontology that contains the OWL 2 translation of a class diagram.

4.2.1 State and State Hierarchy

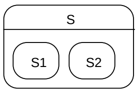
We represent a UML state as a concept representing the objects that have such state active. A concept representing a state will be included in the concept representing all object instances of the class associated to the statechart diagram, since all objects that can have the state active belong to the given class. That is, if the state S belongs to a statechart diagram describing the behavior of the class C, then $S \sqsubseteq C$. We represent this in OWL 2 as follows:

```
Declaration(Class(S))
SubClassOf( S C )
```



State hierarchy is also represented using a concept inclusion. Whenever a substate is active, its containing state is also active. This implies that the concept representing a substate will be included in the concept representing is the parent state, $sub \sqsubseteq S$. This is represented in OWL 2 as `SubClassOf( sub S )`.

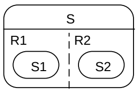
4.2.2 Non-orthogonal States are Exclusive



The UML Superstructure specification requires that if a composite state is active and not orthogonal, at most one of its substates is active ((OMG, 2011), p.564). This means that an object cannot be at the same time in the two concepts representing two exclusive states, i.e., if S_1 and S_2 represents substates of an active and not orthogonal composite state then $S_1 \sqcap S_2 = \bot$. When representing a statechart diagram in OWL 2, the non-orthogonal exclusive states are declared as disjoint, so that they may not able to share any object.

```
DisjointClasses( S1..Sn )
```

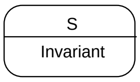
4.2.3 Orthogonal States are Non-exclusive



The UML Superstructure specification requires that if a composite state is active and orthogonal, all of its regions are active ((OMG, 2011), p.564). That is if R_1 and R_2 are concepts representing the two regions of an orthogonal composite state represented by the concept S, then $R_1 \sqcup R_2 = S$. We should note that if S_1 and S_2 represent two substates where $S_1 \sqsubseteq R_1$ and $S_2 \sqsubseteq R_2$, then they are not exclusive and $S_1 \sqcap S_2 \neq \bot$. Due to the open-world assumption of DL, concepts may represent common individuals unless they are explicitly declared as disjoint.

4.3 State Invariant into OWL 2 DL

The UML specification defines a state in a UML diagram as the representation of a specific condition "A state models a situation during which some (usually implicit) invariant condition holds" ((OMG, 2011), p.559-560). We understand from this definition that the invariant condition characterizes the state: if the invariant condition holds the state is active, otherwise if the invariant condition does not hold the state is not active. In our approach we represent an invariant as an OWL 2 concept representing objects that make that invariant evaluate to true. Since the invariant holds iff the associated state is active, the concept representing a state will be the same as the concept representing an invariant. This is represented in OWL 2 as an equivalent class relation between the state and its invariant:



```
EquivalentClasses (S Invariant)
```

Due to the equivalent relationship between the state and its invariant, all objects that fulfill the condition of its state invariant will also be in that specific state.

4.3.1 State Constraints

The UML also allows us to define additional constraints to a state, and names these constraints also state invariants. However, the semantics of a state constraint are more relaxed since it "specifies conditions that are always true when this state is the current state" ((OMG, 2011), p.562). In this sense, the state constraints define necessary conditions for a state to be active, but not sufficient. This means that, the actual state invariant may remain implicit. However, we consider a state invariant as a predicate characterizing a state. That is, a state will be active if and only if its state invariant holds.

4.3.2 A State Invariant Characterizes a State

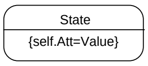
The UML superstructure specification requires that whenever a state is active its state invariant evaluates to true ((OMG, 2011), p.562). A consequence of this is that state invariants should be satisfiable. That is, every state invariant in a statechart diagram must hold in at least one object configuration. Otherwise there cannot be objects that have such state active. Since invariants should be satisfiable, the concept S representing a state should be satisfiable $S \neq \bot$.

4.4 OCL to OWL 2 DL

A state invariant is a runtime constraint on a state in a statechart ((OMG, 2011), p.514). The UML specification proposes the use of OCL to define constraints in UML models, including state invariants. OCL is well supported by many modeling tools (Birgit Demuth, 2009; Garcia and Shidqie, 2007). Unfortunately, in general OCL is not decidable. However, we can avoid undecidability by restricting our approach to a reduced fragment of the full OCL (Queralt et al., 2012a). The use of a limited fragment of OCL to avoid undecidability has been proposed in the past also by other authors (Queralt et al., 2012a; Queralt et al., 2012b).

In this article, we consider OCL constructs using mainly multiplicity, attributes value and boolean operators. The grammar of OCL, supported in our approach is shown in Figure 3.

4.4.1 Attribute Constraints

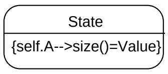


The value of the attribute is accessed in OCL by using a keyword *self* or by using a class reference ((OMG, 2006), p.15), the value constraint of the attribute *Att* is written in OCL as `self.Att=Value`, meaning $\{x|(x, Value) \in Att\}$, where *Value* represents the attribute value. The restriction on the value of the attribute is translated in OWL 2 by using the axiom `DataHasValue`. The OCL attribute value constraint `self.Att=Value` is translated in OWL 2 as:

```
DataHasValue(Att "Value"^^datatype )
```

In above translation, *Att* is the name of the attribute, *Value* is the value of the attribute and it is always written in OWL 2 in double quotes, and *datatype* is the datatype of the attribute *Value*.

4.4.2 Multiplicity Constraints



The multiplicity of an association is accessed by using *size*() operation in OCL ((OMG, 2006), p.144). The multiplicity constraint on the association *A* in OCL is written as `self.A->size()=Value`, where *Value* is a positive integer and represents a number of allowable instances of the range class of the association *A*. We can use a number of value restriction infix operators with *size*() operation such as =, >=, <=, < and >. The multiplicity constraint on an association *A* is defined as $\{x|\#\{y|(x,y) \in A\} OP\ Value\}$, where *OP* is the infix operator and *Value* is a positive integer. The translation of *size*() operation in OWL 2 is based on the infix operator used with the *size*() operation, for example, the OCL constraint `self.A->size()=Value`, in which *A* is the name of an association, ">" is an infix operator and *Value* is a positive integer, translated in OWL 2 as: `ObjectExactCardinality(Value A)`.

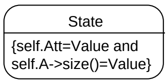
Furthermore, the constructs *isEmpty* and *notEmpty* represent $size() = 0$ and $size() > 0$ respectively. The invariant `self.A->isEmpty()` is translated in OWL 2 as:

```
ObjectExactCardinality(0 A)
```

and the invariant `self.A->notEmpty()` is translated in OWL 2 as:

```
ObjectMinCardinality(1 A)
```

4.4.3 Boolean Operators



The constraints in a state invariant are written in a form of a boolean expression, and joined by using the boolean operators, such as "*and*" and "*or*" ((OMG, 2006), p.144). The binary "*and*" operator evaluates to true when both boolean expressions Ex_1 *and* Ex_2 are true. In our translation this is represented by the intersection of the concepts that represent both expressions $Ex_1 \cap Ex_2$ as `ObjectIntersectionOf(Ex1 Ex2)`. The binary "*or*" operator evaluates to true when at least one of the boolean expression Ex_1 *or* Ex_2 is true. In our translation this is represented by the union of the concepts that represent both expressions $Ex_1 \sqcup Ex_2$. This is represented OWL 2 as `ObjectUniounOf(Ex1 Ex2)`.

⟨OCL-expression⟩ ::= ⟨cond-expr⟩ (⟨logic-op⟩⟨cond-expr⟩)*
⟨logic-op⟩ ::= *and* | *or*
⟨cond-expr⟩ ::= ⟨ref⟩ →size()⟨relational-operator⟩⟨integer-literal⟩
| ⟨ref⟩ →isEmpty() | ⟨ref⟩ → notEmpty()
| ⟨ref⟩⟨relational-operator⟩⟨primitive-literal⟩
⟨ref⟩ ::= self.⟨identifier⟩
⟨identifier⟩ ::= ′{⟨characters⟩} | 0..9 {0..9}′
⟨relational-operator⟩ ::= < | <= | > | >= | <> | =
⟨primitive-literal⟩ ::= ⟨boolean-literal⟩ | ⟨integer-literal⟩
| ⟨string-literal⟩ | null
⟨boolean-literal⟩ ::= true | false
⟨integer-literal⟩ ::= 0..9 {0..9}
⟨string-literal⟩ ::= ′{⟨characters⟩}′

Figure 3: The grammar of the supported OCL fragment.

```
// Class Diagram into OWL 2 DL
Declaration(Class(Article))
Declaration(Class(Review))
Declaration(Class(Withdraw))
Declaration(Class(PublicationRecord))
...
DisjointClasses( Article Review ...)
Declaration(ObjectProperty(review))
ObjectPropertyDomain( review Article)
ObjectPropertyRange( review Review )
...
SubClassOf( Article
ObjectMaxCardinality( 1 review ))
....
Declaration(
DataProperty( WaitingforRevision))
SubClassOf(Article
DataExactCardinality(1 WaitingforRevision))
...
DataPropertyDomain(
WaitingforRevision Article )
..
DataPropertyRange(
WaitingforRevision xsd:boolean )
```

```
//Statechart diagram into OWL 2 DL
Declaration(Class(ArticleReview))
Declaration(Class(ArticleWithdraw))
Declaration(Class(Publish))
SubClassOf( ArticleReview Article )
SubClassOf( ArticleWithdraw Article )
SubClassOf( Publish Article ))
...
DisjointClasses( ArticleReview
ArticleWithdraw Publish )
Declaration(Class(WaitingforReview))
SubClassOf( WaitingforReview ArticleReview )
...
//Invariant of state Publish Start
EquivalentClasses (Publish
ObjectIntersectionOf(
ObjectIntersectionOf(
ObjectExactCardinality(1 review)
DataHasValue(Decision "accept"^^xsd:string ))
ObjectIntersectionOf ( ObjectExactCardinality
(0 withdraw) ObjectExactCardinality
(1 publicationRecord)) ) )
//Invariant of state Publish End
```

Figure 4: The excerpt of the output ontology generated by the translation tool.

5 CONSISTENCY ANALYSIS USING AN OWL 2 REASONING TOOL

We have defined earlier the satisfiability of UML models in Section 3. The consistency analysis of UML models is reduced to the satisfiability of the conjunction of all conditions derived from a model. In order to determine the satisfiability of the conditions represented in UML models, we first translate the UML models into an OWL 2 ontology, then use an OWL 2 reasoner to analyze the satisfiability of translated concepts.

To translate UML models into OWL 2 ontology, we have implemented the translations of class diagrams, statechart diagrams and state invariants discussed in Section 4, in an automatic model to text transformation tool. The implemented translation tool allows us to automatically translate class diagrams, statechart diagrams and state invariants into OWL 2 DL. The translator reads class diagrams, statechart diagrams and OCL state invariants from an input model serialized using the XMI format. The XMI

```
Found 4 unsatisfiable concept(s):
a:Accept
a:ArticleRejected
a:ArticleReview
a:ArticleWithdrawn
```

Figure 5: The satisfiability report of the ontology shown in Figure 4 generated by the OWL 2 reasoner Pellet.

is generated by using a modeling tool. We used Magicdraw to create the example designs used in this article. The output of the translation tool is an ontology file ready to be processed by an OWL 2 reasoner.

As an example, we have translated the class diagram, statechart diagram and OCL state invariants shown in Figure 1 and Figure 2, into OWL 2 DL ontology using the implemented translation tool. An excerpt of the output ontology generated by the translation tool is shown in Figure 4.

5.1 Reasoning

After translating the class diagram, statechart diagram and state invariants into an OWL 2 ontology by using the implemented translation tool, we process the ontology by using an OWL 2 reasoner. The OWL 2 reasoner combines all the facts presented as axioms in the ontology and infers logical consequences from them. When we give the generated ontology to the reasoner, it generates a satisfiability report indicating which concepts are satisfiable and which not. If the ontology has one or more unsatisfiable concept, this means that the instance of any unsatisfiable concept will make the whole ontology inconsistent, consequently, an instance of the class describing an unsatisfiable concept in a class diagram will not exist, or objects will not enter into a state describing an unsatisfiable condition, otherwise viceversa.

In order to analyze the satisfiability of the inconsistent invariants listed in Section 2. The ontology of an example model with inconsistent invariants is validated by using an OWL 2 reasoner name Pellet (Sirin et al., 2007). The satisfiability report of the ontology of UML models with inconsistent state invariants is shown in Figure 5. As explained in Section 4.3, a state invariant characterizes the state ((OMG, 2011), p.559-560). Therefore, the presence of unsatisfiable states in the satisfiability report indicates the existence of inconsistent state invariants in identified states.

5.2 Performance Analysis

In order to determine the performance of the translation and reasoning tools, we conducted an experiment using UML class and statechart diagrams consisting of 10 to 2000 model elements. We use a desktop computer with an Intel Core 2 Duo E8500 processor running at 3.16GHz with 2GB of RAM. The performance tests are conducted for both consistent and mutated models containing inconsistencies introduced by us. For each test, we measure the time required to translate a model from UML to OWL 2 and the time required by the OWL 2 reasoners Pellet (Sirin et al., 2007) and HermiT (Shearer et al., 2008) to analyze the models. The results are shown in Table 1, and in Figure 6.

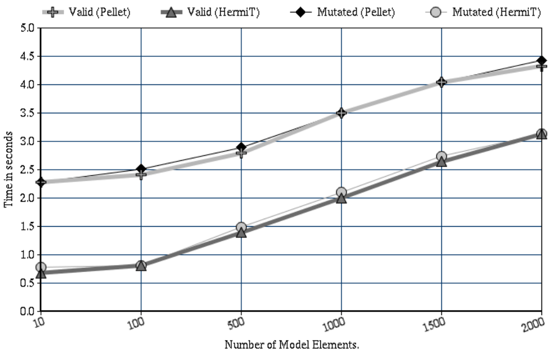


Figure 6: The graph of the total time (Translation time + Reasoning time) to process valid and mutated models.

Table 1: Time taken by the translation tool and reasoning engines to process UML models.

Model Elements	10	100	500	1000	1500	2000
Translation Time	0.08s	0.11s	0.19s	0.30s	0.44s	0.53s
Pellet						
Valid	2.2s	2.3s	2.6s	3.2s	3.6s	3.8s
Mutated	2.2s	2.4s	2.7s	3.2s	3.6s	3.9s
HermiT						
Valid	0.6s	0.7s	1.2s	1.7s	2.2s	2.6s
Mutated	0.7s	0.7s	1.3s	1.8s	2.3s	2.6s

The time complexity of OWL 2 DL with respect to the reasoning problems of the ontology consistency and instance analyzing is NEXPTIME complete (Horrocks et al., 2003). However, the graph (Figure 6) of the performance test shows that the time required to reason about models only grows linearly. This is due to the fact that in our approach we analyze the consistency of class and statechart diagrams without individuals.

6 CONCLUSIONS

In this article we have presented an approach to analyze the consistency of UML class diagrams and UML statechart diagrams with state invariants. The approach is fully automated thanks to the translation tool and the existing OWL 2 reasoners. Since the translation tool accepts standard UML models serialized using the XMI standard, the approach can be easily integrated with existing UML modeling tools.

Our approach is decidable because we restrict ourselves to an admittedly small fragment of OCL. This strategy has been already used for expressing constraints over class diagrams (Cabot et al., 2008; Queralt et al., 2012b). We believe that the use of limited subsets of OCL do not reduce the merits of this and similar approaches even if they cannot be used to process all possible OCL constraints. An analysis tool could in fact integrate different analysis approaches and use the right one depending of the fragment of OCL used in the models.

The performance experiments show that the proposed approach can process relatively large UML models in few seconds by using current reasoning tools on desktop computers. Therefore, we consider that this approach has the potential to be incorporated with existing and future UML modeling tools and offer consistency analysis services that go ahead of what is being offered in current modeling tools.

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