Ontology-based Detection of Inconsistencies in UML/OCL Models

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Abstract: Consistency checking of UML/OCL models is a challenging issue in software development. In this paper, we discuss an OWL/ontology-based method to detect the inconsistencies in the UML/OCL models as the first step of requirement change management. Specifically, we map the UML/OCL models to OWL, so that the consistency of the corresponding ontology can be checked by OWL reasoners automatically. We propose a set of mapping rules to interpret the components of UML state machine diagrams, along with OCL constraints, to OWL DL. Towards this objective, we demonstrate three consistency reasoning tasks over a state machine diagram using OWL reasoners. In each case, the result of reasoning is accompanied by an explanation of the logic behind the decision.

1 INTRODUCTION

There are two main advantages of using an ontology in software engineering. First, ontologies provide common vocabularies of given domains that can be shared between software developers for different software applications. Second, once the model of the software and the user requirements are represented as an ontology in OWL (WC3, 2004), the requirement satisfaction can be verified automatically using an inference engine.

In this paper, we are focusing on the latter issue. However, instead of proving that user requirements are satisfied, we will show some "reasonable assurances" to the developer that the model is correct, reserving full verification of requirement satisfaction as future work.

2 PROBLEM STATEMENT

Unified Modeling Language (UML) is a widely used industry standard language that provides graphical notation for software design specification in the early phases of software development. Systems Modeling Language (SysML) is an extension of a subset of the UML. However, UML/SysML models alone are not expressive enough to represent constraints on the modeling concepts. Object Constraint Language

(OCL) is used to express constraints in UML/SysML models. Many UML/SysML tools support adding OCL constraints in UML class diagrams and SysML block diagrams. However, none of the tools supports the semantics checking of the constraints. In other words, the UML/SysML tools do not check if the model is correct according to these constraints.

To support the software developers with automated reasoning capabilities when developing the model of the software, we use an ontology-based method to reason about the correctness of a UML/SysML model with OCL constraints. Specifically, we map UML class diagrams (or SysML block diagrams), state machine diagrams, and OCL constraints to OWL (WC3, 2004), and check the consistency of the corresponding ontology by running an OWL inference engine. Although significant amount of research on mapping UML models to ontologies has been reported, almost all of the researchers limit their scope of investigation to class diagrams. There is a lack of widely accepted mapping rules for the mapping of UML behavior diagrams to OWL.

In this paper, we propose a set of mapping rules to interpret the components of UML state machine diagrams, along with OCL constraints, to OWL DL. The novelty of our approach is the identification and implementation of a more complete mapping of UML/SysML to OWL, than what is included

with current CASE tools to support deeper model verification. There are a few papers on the mapping of the UML/SysML behavior diagrams to OWL DL, however, they either use a non-OCL logic, a restricted set of OCL operators and/or do not support formal proof. Our mapping rules have two advantages: (1) they show how to translate both basic state machine elements (including states, transitions, events, actions, guards, and triggers) and OCL constraints in the state machine diagrams (including the OCL invariants in states and guards) to OWL, and (2) the OCL to OWL translation rules cover relational operators (e.g equivalent, greater/less than) between variables.

The existing research on consistency checking of UML state machine diagrams focuses on the contradictions between: (1) the UML metamodel and state machine specifications, and (2) state machine diagrams and other types of diagrams. Verification that state machine diagrams are not contradictory with the requirements expressed as OCL constraints is also a very important issue in software development. In this paper, we check for contradictions between OCL constraints in state machine diagrams. We demonstrate this capability on three exemplary inference tasks.

The rest of this paper is organized as follows. In Section 3, we review some of the existing literature related to our work. In Section 4, we show the OWL axiom usage in reasoning about SysML block diagrams. In Section 5, we propose a set of mapping rules to interpret the components of state machine diagrams along with OCL constraints to OWL DL, and demonstrate three reasoning tasks using OWL reasoners. Finally, Section 6 summarizes our work.

3 RELATED WORK

We group our literature review into four categories.

Classification of Inconsistency in UML Models: Consistency checking of UML/SysML models is an important step in MBSE-based system development. The appropriate definitions of types of consistency are still an open research topic, c.f., Ahmad and Nadeem (2010); Elaasar and Briand (2004); Usman et al. (2008). One of the UML consistency classifications is horizontal vs. vertical consistency. Horizontal consistency, also called intra-model consistency, means the lack of contradictions between different diagrams at the same level of abstraction. Vertical consistency, also called inter-model consistency, means the lack of contradictions between different diagrams at different levels of abstraction. Another

basic classification of consistency in UML is syntactic vs. semantic consistency. Syntactic consistency refers to the relation between UML diagram specifications and a UML metamodel, whether the syntax of a given diagram is compatible with the syntax prescribed by the metamodel. Semantic consistency refers to the meaning of UML diagrams, i.e., to the notion of *truth* - whether any contradictions in the model do not exist and whether a concept can be instantiated. Other methods of consistency classification were also discussed in the literature, e.g., static versus dynamic consistency, multi-level consistency, and the nature of errors.

In this paper, we focus on the consistency of UML models that include requirements expressed in OCL. Since the OCL constraints capture the semantics of the domain, our approach falls in the semantic validation category.

Consistency Checking Via Mapping to Formal Languages: Many approaches rely on the mapping UML/SysML models to a formal languages and automatic proof engines that are used for reasoning on these models. While many recent papers propose mapping of UML to OWL, most of the papers seem to ignore the fact that UML and OWL have different semantics. This issue was first discussed in (Baclawski et al., 2001), where the authors identified similarities and differences between UML and DAML (DARPA Agent Markup Language). To close the gap between the two representations, the authors proposed extending UML by adding two metamodel elements called *Property* and *Restriction*, where a property is a grouping of association ends and a restriction is a classifier for objects. The recommendation from the (Baclawski et al., 2001) paper has not materialized primarily due to the fact that UML has not been modified as suggested in the paper. Moreover, DAML became OWL.

UML2Alloy (Anastasakis and Ray, 2010; Przigoda and Drechsler, 2016) maps UML/OCL models to Alloy notations, and then the Alloy model is automatically analysed by the Alloy Analyzer. Alloy is an object modeling language based on First Order Logic (FOL), offering declaration syntax compatible with graphical object oriented models, and state-based formulas. However, Alloy models do not provide semantic notations which are necessary during the analysis phase of software development (Dwivedi and Rath, 2018).

USE (Gogolla et al., 2008, 2007) includes an interpreter for a subset of UML and OCL. It provides its own UML/OCL user interface and lets one check constraints (invariants and pre- and post-conditions). That is, it checks model states (snapshots) making

sure invariants are not contradictory. However, this is not a formal system and it uses a custom UI that does not support XMI import/export.

Rehman et al. (Latif et al., 2018, 2019) modeled a smart parking and a sewage systems using UML activity diagrams, translating them to automata-based models, and then to temporal logic of actions. A (TLA)-based formal method was utilized to validate and verify system properties using the TLA+ toolbox (Lamport, 2021). The toolbox includes a proof system and a high level language to generate TLA code. TLA+ is a good tool for verifying code simulating state machines, it is not clear how it could be used for model analysis, which was our objective.

Automated Reasoning on UML/OCL conceptual Schemas (AuRUS) (Rull et al., 2013) is a standalone application which allows verifying and validating UML/OCL conceptual schemas specified in ArgoUML. Verification consists in determining whether the schema satisfies a set of well-known desirable properties such as class liveliness or non-redundancy of integrity constraints. However, AuRUS only validates the structural part of a schema. Validation of the behavioral part of a schema is not supported.

There are many other methods surveyed in (Ahmad and Nadeem, 2010; Usman et al., 2008) that are based on a formal language. In particular, the authors considered mapping UML models to DL. None of the methods reviewed in that paper check the consistency of the OCL constraints. Some researchers pursue verification of consistency, e.g., Filipovikj (2019); Mahmud et al. (2016), but not of UML/SysML models.

Ontology-based Consistency Checking: In (Parreiras et al., 2007), the authors investigate the method called TwoUse to integrate a UML model and an OWL ontology. Since OWL classes can not be exploited through OCL expressions, the authors propose an extension to the OCL basic library, called OCL-DL, to permit operations to call the OWL reasoner. In OCL-DL, the authors propose new operations which rely on reasoning engine services to extend the boundaries of OCL towards OWL. However, their method only focuses on UML class diagrams.

In (Berardi et al., 2005), the authors represent class diagram operations using three ways: (1) FOL n-ary predicate that has to satisfy some FOL assertions. (2) DLR-ifd (variation of DL) where the operation is represented as an n-ary relation. (3) ALCQI (variation of DL) where the approach is based on reification and an operation is expressed as an atomic concept - ALCQI roles. Our approach to class

diagram mapping is in line with (Berardi et al., 2005). **Mapping Behavior Models to OWL DL:** The method in (Van Der Straeten et al., 2002) translates UML state machines and OCL constraints to DLR - an expressive Description Logic (DL) that supports n-ary relations. The basic idea is that the states and transitions in a state diagram are mapped to primitive concepts in DL. We have not found tool support for the translation. Also, the translation of OCL to OWL does not allow relational operators between variables.

In (Gröner and Staab, 2010), the authors describe a transformation of UML statechart primitives to OWL DL. In their transformation, a specific state is defined by a class expression constrained by transitions and state conditions. A specific transition is defined by an intersecting class expression standing for the source, target, event and guard of this transition. However, this work does not support translation of OCL constraints.

In (Khan and Porres, 2015; Khan et al., 2013), the authors translate both the UML class and statechart diagrams of a model to a single ontology, and analyze the consistency and satisfiability of the model using OWL reasoners. However, the authors do not provide any translation of transitions in the statechart diagram. Moreover, translation of OCL to OWL does not allow relational operators between variables.

The method in (Belgueliel et al., 2014) represents state machine using OWL individuals. It is difficult to extend this method for OCL support, since the mapping of OCL to OWL that we use is class-based.

The detailed comparison of theses mapping rules is shown in Table 2.

4 OWL REASONING ABOUT SysML BLOCK DIAGRAMS

An ontology is an explicit, formal specification of a shared conceptualization (Gruber, 1993). Ontologies include five basic components to represent the knowledge of a domain: (1) Classes: groups of things that share common characteristics; (2) Relations: the ways in which classes can be related to one another; (3) Constraints: determining which values are allowed for relations; (4) Axioms: logical statements or assertions about classes, relations, and constraints; (5) Instances: the things that the ontology describes. Web Ontology Language (OWL) is a family of standardized ontology languages with formal semantics to formalize ontologies. Protégé (Stanford University, 2020) is a popular open-source ontology editor and knowledge base framework. We used Protégé to develop our ontologies.
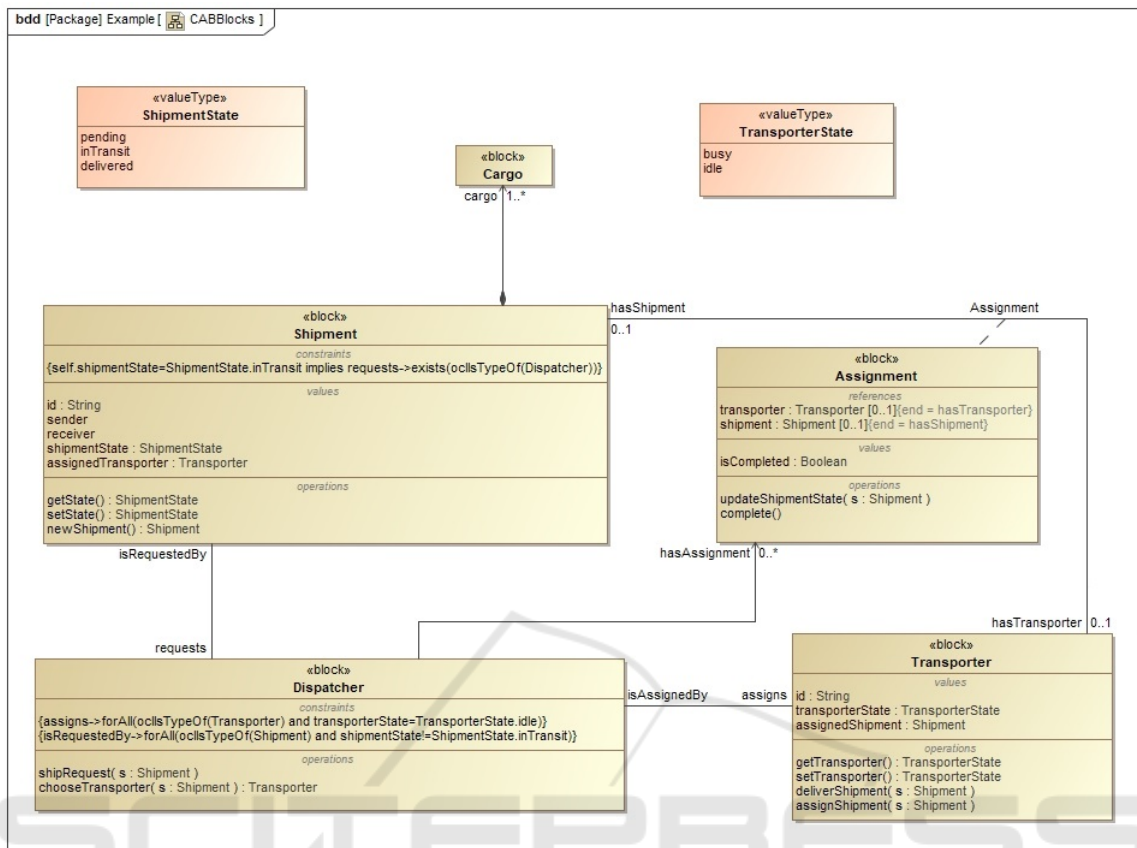
Figure 1: SysML Block Diagram of the CAB Model.

We used the Cameo Concept Modeler plugin (NoMagic, 2021) for Cameo Enterprise Architecture to translate SysML block diagrams to OWL. Then we used rules to translate OCL contraints to OWL. In this paper, we only consider a subset of OCL constraints, namely OCL invariants. OCL invariants were manually translated into OWL 2 DL axioms based on (Parreiras et al., 2007) and (Fu et al., 2017). Specifically, for a block diagram, the OCL invariants of a block are translated into OWL object property restrictions. OWL DL provides three types of class axioms to construct a class description: *SubclassOf*, *EquivalentClasses*, *DisjointClasses* that can be used for checking consistency.

Generalization associations between two blocks are translated into *SubclassOf* axioms of the corresponding OWL classes. Moreover, OCL invariants of a block are translated into *SubclassOf* axioms of the corresponding OWL class. In DL, we represent this as $C_1 \sqsubseteq C_2$. When such a subclass axiom is part of an OWL model, for any individual x of C_1, the fact *(x rdf:type C_2)* is inferred by an OWL reasoner. If the class description of C_1 has conflicts with the class description of C_2, the OWL reasoner will detect this as an inconsistency.

Generalizations with the "Equivalent Class" stereotype in SysML are translated into *EquivalentClass* axioms of the corresponding OWL classes. In DL, we represent this as $C_1 \equiv C_2$. If the class description of C_1 has conflicts with the class description of C_2 (i.e., the sets of the individuals from these two classes do not fully overlap), the OWL reasoner will detect this as an inconsistency.

Dependencies with the "Disjoint With" stereotype in SysML are translated into *DisjointClasses* axioms of the corresponding OWL classes. In DL, we represent this as $C_1 \equiv \neg C_2$. In such a case, if the class description of C_1 has any overlap with the class description of C_2, the OWL reasoner will detect this as an inconsistency.

Here we consider an example based on the Cloud Agility Baseline (CAB) (DARPA, 2021) that SNC and Northeastern developed to provide an adaptable framework which can be molded to meet typical Logistics and Cloud applications and changes to those requirements. Figure 1 shows the SysML block diagram of the CAB model. The question we are investigating in this paper is - how do we verify the correctness of the CAB model, e.g., are the state machines of the CAB correct?
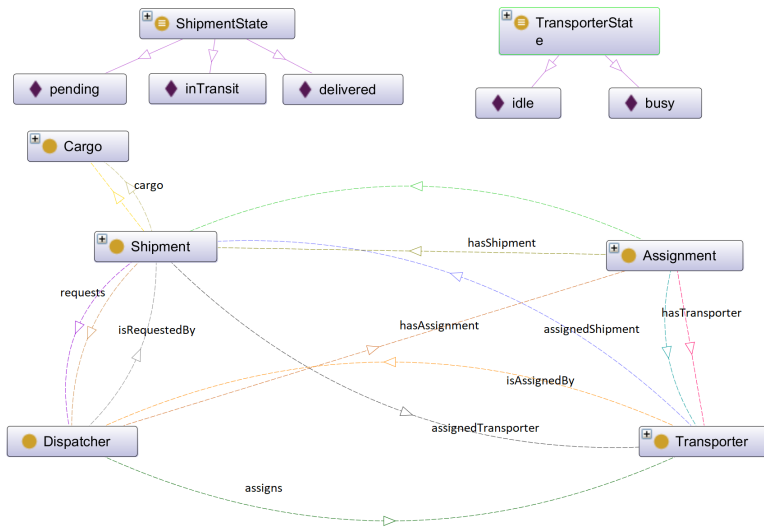
Figure 2: Main Structure of the CAB Ontology.

Table 1: Principles of mapping of OCL to OWL.

Invariant	OWL DL
Context C_1 : p → $forAll(oclIsTypeOf(C_2))$	$C_1 \sqsubseteq \forall p.C_2$
Context C_1 : p → $exists(oclIsTypeOf(C_2))$	$C_1 \sqsubseteq \exists p.C_2$
Context C_1 : $attr1 = C_2$	$C_1 \sqsubseteq \forall p.C_2$
Context C_1 : $attr1! = C_2$	$C_1 \sqsubseteq \neg \exists p.C_2$

Cameo translates the six blocks in the CAB SysML model and the associations between them to the classes and properties in the CAB ontology. Figure 2 shows the main structure of the CAB ontology in Prot*égé*. However, the Cameo mapping-to-OWL capability is very limited and the automatic translation lost some information in translation. We extended the automatically generated CAB ontology by mapping the OCL constraints in the Dispatcher block and the Shipment block into OWL restrictions for the corresponding classes manually (shown in Figures 3 and 4). In this step, we followed the mapping principles shown in Table 1. Finally, we ran the OWL reasoner. It identified the semantic inconsistency of the model: the Shipment block is equivalent to Nothing, i.e., the OWL class is not satisfiable (it cannot have any individuals).

5 MAPPING RULES

The main concepts of state machines are *state, transition, event, guard* and *action*. These concepts are mapped to OWL following the rules shown in Table 2. A simple state is mapped to a class

expression in OWL. The classes are constrained by transitions and *state invariants* expressed in OCL. All the state classes are disjoint. In OWL, each transition of a state machine diagram is represented by an intersection of class expressions for the source state, target state, event and guard of this transition. In addition, our translation introduces relational operators between variables.

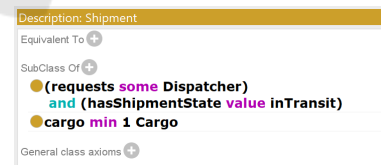Figure 3: OWL Restrictions for the Dispatcher Class.

Figure 4: OWL Restrictions for the Shipment Class.

5.1 A Mapping Example

The statechart diagram in Figure 5 describes the behavior of the Dispatcher block from Figure 1. The six states are mapped to six OWL classes. The OWL DL representations of the OCL constraints on the states are shown in the following DL expressions.

$$Allocating \equiv Waiting \sqcup GettingTransporters \sqcup MakingAssignment \quad (1)$$

Table 2: UML State Machine Diagram to OWL Mapping Rules Comparison.

State Machine Component		Gröner and Staab (2010)	Van Der Straeten et al. (2002)	Khan and Porres (2015)	Belgueliel et al. (2014)	Our Mapping Rule
State	Simple State	Class	Class	Subclass of the class of the object	Individual	Class
	Composite State	Superclass of substate classes	Superclass of substate classes	Superclass of substate classes	Individual	Superclass of substate classes
	Initial State	Class	Class	Class	Individual	Class
	Final State	Class	Class	Class	Individual	Class
	OCL invariants	None	None	OWL object property restrictions	None	OWL object property restrictions
Transition		Class	Class	None	Individual	Class
Event		Class	Class	None	Individual	Class
Action		None	Class	None	Individual	Class
Guard		Class	Class	None	Individual	Class
Guard expressed in OCL invariants		None	None	None	None	OWL object property restrictions

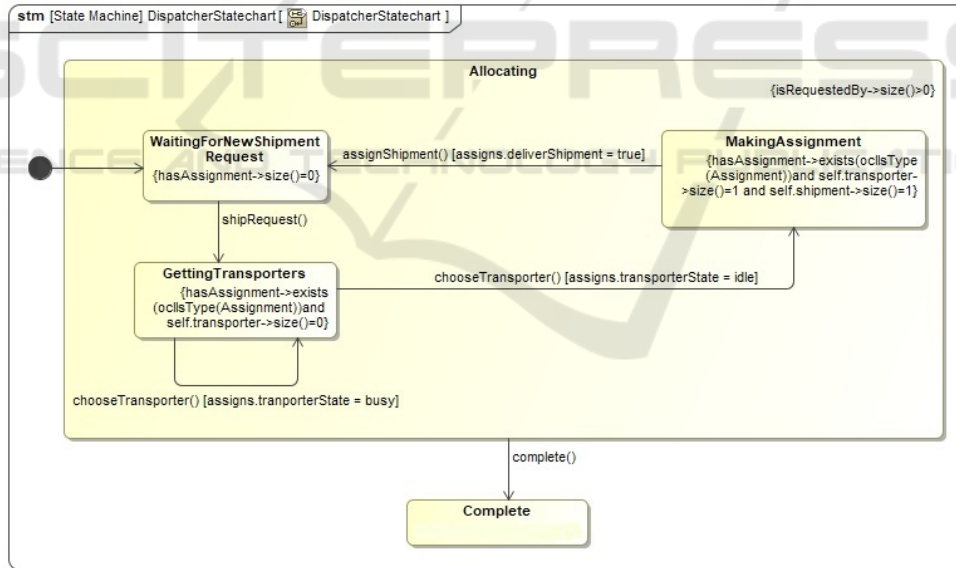Figure 5: Dispatcher Statechart.

$$Allocating \sqsubseteq \exists isRequestedBy.Shipment \quad (2)$$

$$Complete \sqsubseteq \forall isRequestedBy.1Shipment \quad (3)$$

$$Waiting \sqsubseteq \forall hasAssignment.0Assignment \quad (4)$$

$$GettingTransporters \sqsubseteq \exists hasAssignment.(Assignment \sqcap \geq hasTransporter.1Transporter) \quad (5)$$

$$MakingAssignment \sqsubseteq \exists hasAssignment.(Assignment \sqcap \forall hasShipment.1Shipment \sqcap \forall hasTransporter.1Transporter) \quad (6)$$

The six transitions are also mapped to six OWL classes. The transition from *Waiting* to *GettingTransporters* is triggered by the event *shipRequest*. So the transition class

WaitingToGettingTrans is defined as:

$$WaitingToGettingTrans \equiv \\ \exists fsm.triggeredBy.\{shipRequest\} \quad (7)$$

$$WaitingToGettingTrans \sqsubseteq \exists fsm.hasSource.Waiting \\ \sqcap \exists fsm.hasTarget.GettingTransporters0 \quad (8)$$

GettingTransporters state has two outgoing transitions. After the operation *chooseTransporter* of the dispatcher is invoked, if the returned transporter state is busy, the state stays at *GettingTransporters*. Otherwise, the state transits to *MakingAssignment*. So the two transition classes are defined as:

$$GettingTrans \equiv \\ \exists fsm.triggeredBy.chooseTransporter \\ \sqcap \exists(fsm.hasGuard.fsm.EvalCmp.EQ \quad (9) \\ \sqcap \exists fsm.hasLeftExpr.\{transporterState\} \\ \sqcap \exists fsm.hasRightExpr.\{busy\})$$

$$GettingTrans \sqsubseteq \\ \exists fsm.hasSource.GettingTransporters \quad (10) \\ \sqcap \exists fsm.hasTarget.GettingTransporters$$

$$GettingTransToMakingAssignment \equiv \\ \exists fsm.triggeredBy.chooseTransporter \\ \sqcap (fsm.hasGuard.fsm.EvalCmp.EQ \quad (11) \\ \sqcap \exists fsm.hasLeftExpr.\{transporterState\} \\ \sqcap \exists fsm.hasRightExpr.\{busy\})$$

$$GettingTransToMakingAssignment \sqsubseteq \\ \exists fsm.hasSource.GettingTransporters \quad (12) \\ \sqcap \exists fsm.hasTarget.MakingAssignment$$

From the state *MakingAssignment*, after the dispatcher invokes the operation *assignShipment*, if the *deliverShipment* is true, then the state of the dispatcher goes back to *Waiting*.

$$MakingAssignmentToWaiting \equiv \\ \exists fsm.triggeredBy.assignShipment \\ \sqcap \exists(fsm.hasGuard.fsm.EvalCmp.EQ \quad (13) \\ \sqcap \exists fsm.hasLeftExpr.\{deliverShipment\} \\ \sqcap \exists fsm.hasRightExpr.\{true\})$$

$$MakingAssignmentToWaiting \sqsubseteq \\ \exists fsm.hasSource.MakingAssignment \quad (14) \\ \sqcap \exists fsm.hasTarget.Waiting$$

5.2 OWL Reasoning with State Machine Diagrams

In order to check the consistency of the state machine in Figure 5, we translate the state machine along with OCL constraints to OWL (as shown in Section 5.1). In order to show different types of inconsistencies of constraints, we defined three reasoning tasks.

The first OWL reasoning task is to check if the OCL invariants of all the states are consistent. The state invariants that may cause the object violate the constraints imposed on state diagrams in the UML superstructure specification of state machine are considered to be inconsistent invariants. For example, for the composite state *Allocating*, the OCL constraint of the state invariant is:

$$isRequestedBy -> size() > 0 \quad (15)$$

which means the dispatcher is in *Allocating* state if it is requested by at least one shipment (Figure 6). The *Waiting* state is a substate of *Allocating*. The substate should not have a conflicting invariant with the composite state. Adding the following invariant to the *Waiting* state:

$$isRequestedBy -> size() = 0 \quad (16)$$

would imply being in the *Waiting* state even if there was no request by any shipment (Figure 7). Thus, such two OCL constraints are inconsistent, and thus there can not be a state individual that can satisfy both the constraints of *Allocating* and the constraints of the *Waiting* states. When we run the OWL reasoner in Protégé, it will identify the semantic inconsistency of the OWL axioms in *Allocating* class and *Waiting* class.
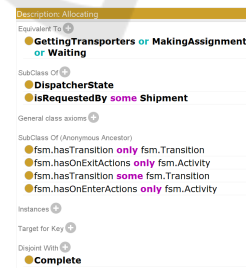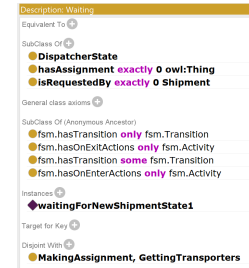

Figure 6: Allocating.　　　Figure 7: Waiting.

The second OWL reasoning task is to check whether only one transition can be taken out of a state, i.e., whether the state machine is deterministic. For a state with more than one possible outgoing transition, e.g., *GettingTransporters*, the state that has two outgoing transitions *GettingTrans* and *GettingTransToMakingAssignment*, adding the guard:

$$assigns.transporterState = busy \quad (17)$$

to both transitions, would make the choice of a transition not unique. In OWL, two outgoing transitions are represented by two disjoint transition classes and should have disjoint guards. Otherwise, the OWL reasoner will identify semantic inconsistency because an individual can not belong to both a type and its complement. The inconsistent result is shown in red in Figures 8 and 9.
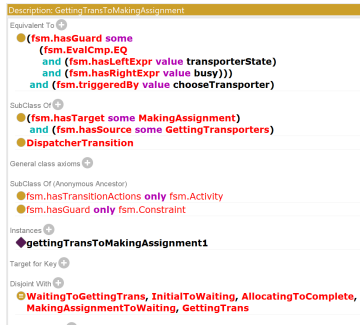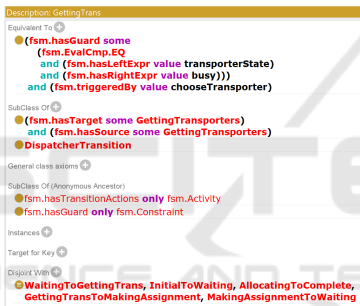

Figure 8: Outgoing Transition1.

Figure 9: Outgoing Transition2.

The third OWL reasoning task is to check if the state machine contains deadlocks. A deadlock happens when two or more processes have conflicting resource needs. In this paper, we consider a simple deadlock case: for a state with only one outgoing transition, the guards on this outgoing transition of a state are mutually exclusive. In other words, if the guards on the only outgoing transition of a state can not be satisfied at the same time, the state machine for the object will be stuck in this state. For example, for the transition from *MakingAssignment* to *Waiting*, if we add the guards as follows:

$$assigns.deliverShipment = true,$$
$$assigns.deliverShipment = false \qquad (18)$$

once the state machine of the dispatcher object gets into *MakingAssignment*, it will not be able to get out of this state because the *deliverShipment* attribute can not be both *true* and *false* at the same time. When we run the OWL reasoner, it will identify the semantic inconsistency of the OWL axioms in the

MakingAssignmentToWaiting class that represents the transition, as shown in red in Figure 10.
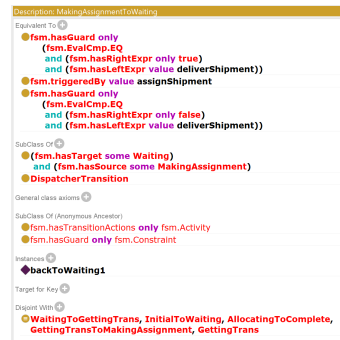

Figure 10: *MakingAssignmentToWaiting* Transition.

6 CONCLUSIONS

In this paper, we discuss an ontology-based method to reason about the correctness of UML/SysML models that include OCL constraints on state machines. Specifically, we map the UML/SysML models with OCL constraints to OWL and check the consistency of the corresponding ontology by running an OWL inference engine. We propose a set of rules for mapping components of UML state machine diagrams along with OCL constraints to OWL DL. We also demonstrate three examples of reasoning tasks in which OWL axioms are used for consistency checking of state machine diagrams. Our work is aimed at providing the software developer with some reasonable assurances about the correctness of the model in the system modeling stage of software development. This is the first step of requirement change management. In the future, we plan to extend the scope of our approach to a more complete and automatic verification of UML state machine specifications with OCL constraints as well as both theoretical analysis and experimental validation of the correctness of the mapping rules.

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