Using the Base Semantics given by fUML for Verification

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Abstract: The lack of formal foundations of UML results in imprecise models since UML only defines graphical notations, but not their formal semantics. However, in safety-critical applications, formal semantics is a requirement for verification. Semantics for the key parts of activities and classes of UML is defined by the semantics of a foundational subset for executable UML models (fUML). Moreover, the base semantics given by fUML defines the formal semantics of UML. In this paper, we evaluate a subset of the base semantics given by fUML covering its formal definition and its use for verification. From the practical perspective, we show with a simple example how the base semantics can support formal verification through theorem proving. The initial results show that the base semantics, when mature, can play an important role in the formal verification of UML models.

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1 INTRODUCTION

Simulation and verification of models is the cornerstone of any model-driven development (MDD). Supporting a large number of MDD methods, Unified Modeling Language (UML) (OMG, 2011) and its derivatives have demonstrated a capability for top-down design refinement for large-scale systems. However, while UML is expressive, the lack of formal foundations of UML results in imprecise models, since UML only defines the syntax of diagrams, but not their formal semantics (Derler et al., 2012; Fecher et al., 2005).

A major focus of systems and software engineering has considered how to introduce precision in the approaches based on UML through formal methods. This introduction can be a requirement when dealing with safety-critical systems; e.g., the IEC 61508 (functional safety of electrical/electronic/programmable electronic safety-related systems) defines formal methods as highly recommended techniques for the highest safety integrity level. Furthermore, DO-178C (software considerations in airborne systems and equipment certification) addresses formal methods as a complement to testing. Although there are languages with a formal semantics, there are no modeling languages with widespread use in systems and software engineering community that have the attraction of UML (Graves, 2012). Accordingly, this paper focuses on the evaluation of a formal foundation in UML concerning behavioral definitions.

Behavior is defined in UML (OMG, 2011) mainly by means of activity diagrams, sequence diagrams, and state machine diagrams, which do not have formal semantics (Derler et al., 2012) and, in general, are also not executable. Behavioral definitions could evolve with the semantics of a foundational subset for executable UML models (fUML) (OMG, 2009), which consists of the key parts of activities and classes. Hence, this version of specification defines semantics, which includes an interpreter and a formal definition of the semantics called *the base semantics*. On the contrary, there are research papers (Benyahia et al., 2010; Perseil, 2011) stating that fUML is not yet suitable for behavioral modeling of safety-critical systems. The reasons can be classified as follows: (1) current tools do neither allow the use of model-checking nor theorem proving (Perseil, 2011), and (2) the execution model is often nondeterministic (Benyahia et al., 2010). In the following, we explore reason (1) in detail.

In this paper, we evaluate a subset of the base semantics (we present this one in Section 4) covering its formal definition and its useage for theorem proving. The major contributions of this work are: (1) it

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shows how the base semantics can support theorem proving, providing one solution for the deficiencies found by (Perseil, 2011); (2) it detected issues in the fUML specification (OMG, 2012) (see Appendix), which suggests to enhance the specification. The initial results show that the base semantics, when mature, can play an important role in the formal verification of models.

The remainder of this paper is organized as follows. In Section 2, related works are explored; in Section 3, the necessary background is presented; in Section 4, we define and evaluate a subset of the base semantics for verification; in Section 5, we discuss the results. Finally, conclusions are shared in the last section.

2 RELATED WORKS

There is a large number of research papers about semantics for models defined using UML. UML and fUML share the definitions about activities. Therefore, every research that has defined semantics for behavior based on activities is directly related to fUML. Considering this relationship, works focused on behavioral semantics for UML, and fUML, can be classified as follows: (1) definition of an operational semantics, (2) translation to other models, and (3) directly defining a model of computation (MoC).

The first class has led to definitions of the operational semantics for activities. (Jarraya et al., 2009) presented a structural operational semantics (SOS) (Plotkin, 1981) for a subset of activity diagrams of systems modeling language (SysML) – a derivative of UML. This subset comprised control nodes and a generic action. The semantics covered advanced control flows such as unstructured loops and concurrent control flows, and model checking was applied for verification purposes. Focused on reactive systems, (Kraemer and Herrmann, 2010) presented an operational semantics for a subset of activity diagrams of UML. This subset included one action representing method calls that are executed in one time unit. Focusing on control flows, this work defined time and queues for synchronization, and applied model checking for verification. (Grnniger et al., 2010) defined a formal semantics for a subset of UML activity diagrams, using semantics variation points. This work stated that all definitions, including the abstract syntax, should be encoded in machine-readable form, allowing the use of a theorem prover. (Knieke et al., 2012) proposed common constructs for the definition of operational semantics for a subset of activity diagrams. The subset covered the actions: *CallBehaviorAction*, *SendSignalAction* and *AcceptEventAction*. In this case, semantics was described through algorithms defined using pseudo-code, and did not comprise object flows.

A broad set of works adheres to translation through definition of a mapping between UML and a formal language. (Abdelhalim et al., 2012) defined a method that receiving state machine diagrams and activity diagrams (according to fUML) applied a transformation to communicating sequential processes (CSP). Later, the method used a model checker to verify the resulting CSP representation. This work focused on maintaining the behavioral consistency between state machine diagrams and activity diagrams. (Perseil, 2011) suggested that a subset of action language for fUML (Alf) (OMG, 2013a) – the relationship between Alf and fUML is explained in Section 3 – should be translated to PlusCal, which has precise semantics defined by a translation to temporal logic of actions (TLA) so that also the model checker of TLA can be used for verification. (Maoz et al., 2011) defined a translation from UML activity diagrams to a labeled transition system described using the language of the SMV model checker. The subset included control nodes and a generic action.

Concerning MoCs, (Benyahia et al., 2010) shows that fUML and Alf are not directly applicable to safety-critical systems because the MoC defined in the fUML execution model was sequential and non-deterministic. In spite of variation points provided by fUML, this work recognized that they were not powerful enough to change the MoC, and an alternative extension of the core execution model was presented to accommodate different MoCs. (Gerlinger Romero et al., 2013) proposed constructs to change the MoC of the fUML introducing the synchronous-reactive MoC. (Combemale et al., 2013) presented an alternative to define domain-specific languages through the combination of semantics of languages and MoCs. The case study was fUML combined with two different versions of the discrete-event MoC, one sequential and another concurrent.

However, to the best of our knowledge, we have not found works about the base semantics defined in fUML, the relationship between it and other approaches for semantics definition (Plotkin, 1981; Hoare, 1969), and how to use it for verification.

3 BACKGROUND

This section presents a review of the OMG (Object Management Group) specifications related to fUML, the base semantics, and its purpose.

3.1 OMG Specifications

In UML, actions are the fundamental units of behavior, and are used in activities to define fine-grained behaviors (OMG, 2011). Considering this, fUML selected part of actions defined in UML to model behavior, and part of expressiveness of classes to model structure. The specification defines four elements for the language: (1) abstract syntax, (2) model library, (3) execution model, and (4) base semantics (OMG, 2012). The specification does not define a concrete syntax, so the only syntax available for defining user models is the graphical notation provided by UML, namely activity diagrams, and class diagrams.

The abstract syntax is a subset of UML with additional constraints, so a well-formed model is one that meets all constraints imposed on its syntactic elements by the UML abstract syntax as well as all additional constraints imposed on those elements by the fUML abstract syntax. These constraints are the equivalent of the static semantics according to fUML (OMG, 2012). Therefore, fUML does not define static semantics, i.e., context-sensitive constraints which define a well-formed model.

The model library defines the primitive types, primitive functions and, a way to interact with the environment (input and output).

The execution model is an interpreter written in fUML (circular definition). The interpreter is defined using core elements (nodes, classes, and edges) of fUML that together form the base UML (bUML). Instead of using activity diagrams, the interpreter is defined as equivalent code in Java. To support that, a mapping from Java to activities is defined, considering only bUML. The execution model is defined to support extensions, what is pursued using two techniques: (1) defining explicit variation points, which are: event dispatching scheduling (used in the inter-object communication), and polymorphic operation dispatching; (2) leaving three semantics elements unconstrained, namely, timing, concurrency, and inter-object communication. Base semantics breaks the circular definition of fUML providing a set of axioms that constrains the execution.

Base semantics covers elements in bUML, and is specified in first order logic based on process specification language (PSL). PSL provides a way to disambiguate common flow modeling constructs in terms of constraints on runtime sequences of behavior execution. A desired behavior is specified by constraining which of the possible executions is allowed (Bock and Gruninger, 2005; NIST, 2013). PSL and base semantics are defined using Common Logic Interchange Format (CLIF) (ISO, 2007).

Alf provides a textual concrete syntax for fUML (OMG, 2013a). It is an action language that includes primitive types (including real numbers), primitive actions (e.g., assignments), and control flow mechanisms, among others. It is object-oriented, and it is an imperative language (like C and Java). The execution semantics for Alf is given by mapping the Alf abstract syntax to the abstract syntax of the fUML (OMG, 2013a).

Fig. 1 shows relationships between these OMG specifications, where fUML is positioned in the center, offering formal semantics for an executable subset of UML (bottom), and supporting the textual action language Alf (top).

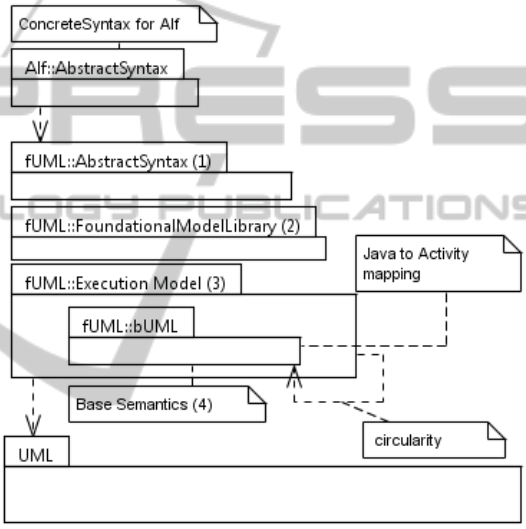

Figure 1: Relationships between OMG specifications.

3.2 Base Semantics

As discussed in the previous subsection, fUML offers an interpreter, which can be extended or completely replaced, e.g., to address scattered scheduling algorithm (Combemale et al., 2013) or nondeterminism (Benyahia et al., 2010).

The specification states that the conformance for an interpreter would be demonstrated by a formal proof that it respects all the definitions of the base semantics ((OMG, 2012); pp. 7). In order to understand how a formal proof could be evaluated for a fUML interpreter, Fig. 2 presents the relationships between abstract syntax, execution model, semantic domain, and base semantics.

Considering the package *Semantics*, the execution model defines the semantic domain (which types an execution manipulates, e.g., *ActivityExecution, Object, Reference*), and an interpreter (an algorithm) that

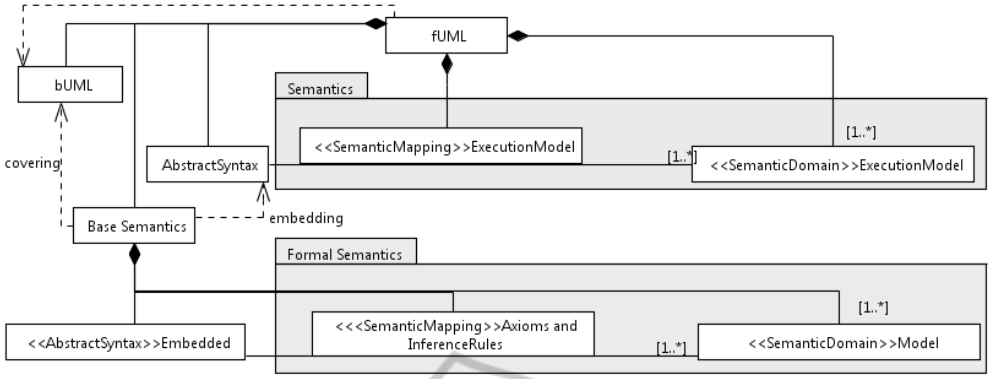

Figure 2: Relationships between fUML and base semantics.

maps instances of the abstract syntax to the semantic domain (in fact, part of the execution model in fUML). This semantic mapping defines the meaning of a given activity.

In Fig. 2, the base semantics depends on the abstract syntax, and is defined to formalize (using first-order logic) the semantic mapping from abstract syntax to the semantic domain without taking into account the particular interpreter offered by the execution model (recall that the base semantics only covers bUML elements). The technique applied to define this formal semantic mapping is called embedding (Fikes et al., 2001).

Embedding is a technique to formalize a language, where the abstract syntax and the semantic domain are directly used in the axiomatization of the semantic mapping. This semantic mapping is defined by a set of axioms and inference rules. Furthermore, a complementary set of inference rules is defined considering the abstract syntax, i.e., some syntactical patterns are explicitly defined to support the inference rules of the semantic mapping.

The base semantics does not formalize the abstract syntax, which would demand a second order logic that could only be emulated by CLIF with restrictions (ISO, 2007).

Therefore, the package *Formal Semantics* defines a set of axioms and inference rules that maps a formal version of activities, defined using the embedded abstract syntax, into a formal version of the semantic domain.

A formal version of the semantic domain is called *model* by logicians. Indeed, (Graves, 2012) recognized that the use of the word *model* is different in the modeling community and in the logic community. For the former, *model* is a representation of the system under consideration (source); whereas *model* is a consistent interpretation for a given set of axioms (result) for the second one.

In summary, CLIF offers the logic syntax, the base semantics provides a set of axioms and inference rules that together with embedded user axioms describing an activity form a mathematical theory. As envisioned by fUML (OMG, 2012), this mathematical theory should be used to evaluate formal properties of an interpreter. Nonetheless, the same theory can be used to verify properties of fUML models applying the theorem proving approach.

4 VERIFICATION USING THE BASE SEMANTICS

This section starts with an example to clarify the concepts introduced in the previous section. Afterwards, a subset of the base semantics, a rationale for this selection, the relationship with other approaches for semantic definition, and a proof using the presented example is shown.

4.1 Example

Considering the representation of a user definition using abstract syntax (a model according to modeling community), Fig. 3 shows an activity diagram (I) considering the fUML abstract syntax. It defines an activity named *Main* with a *ValueSpecificationAction* that shall produce the value $1 \in \mathbb{Z}$ at *OutputPin* named *variableX*. The same activity is presented using an object diagram (II), which shows instances of the abstract syntax and their relationships. Part of the formal description for the same diagram is exhibited in (III) – BS, which uses the embedded version of the abstract syntax. From the 30 formulas needed to describe the activity, 4 are presented. For example, the action is represented as a unary relation *(buml:ValueSpecificationAction Main.ValueSpecificationAction1)*, meaning that *Main.ValueSpecificationAction1* is a *ValueSpeci-*

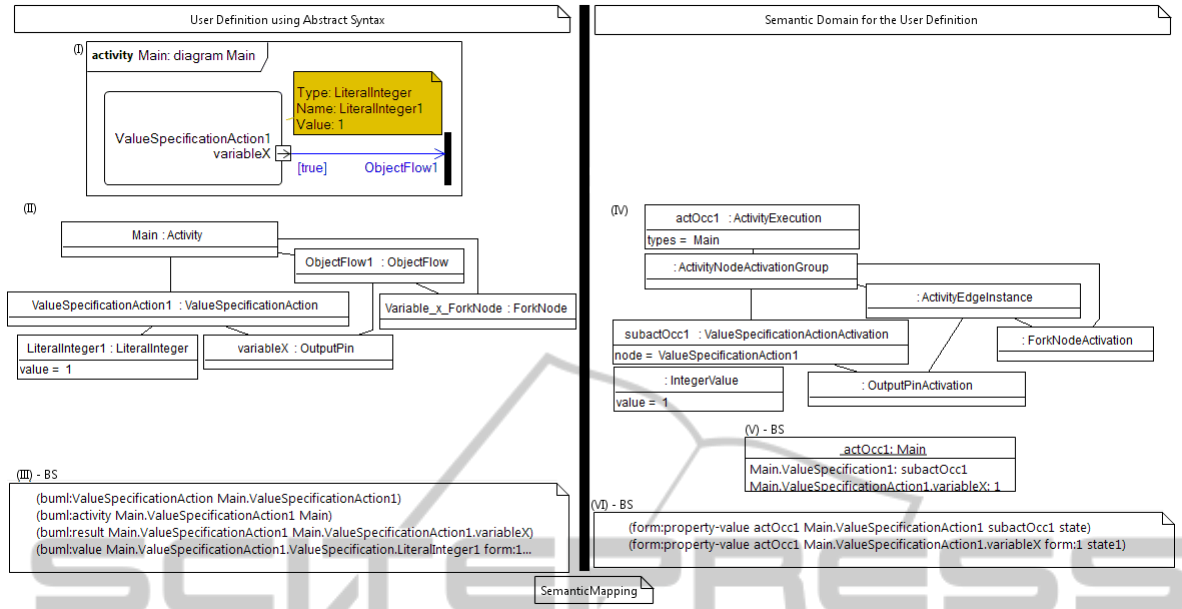

Figure 3: Relationships between fUML and base semantics, considering a user definition.

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ficationAction, and the association owned by the *ActivityNode* between it and the activity *Main* is represented by a binary relation *(buml:activity Main.ValueSpecificationAction1 Main)*.

Considering the semantic domain for the previous discussed user definition, Fig. 3 (IV) presents an object diagram for one execution, according to execution model of fUML (OMG, 2012). For example, one instance of class *ActivityExecution* identified by *actOcc1* having *types* as *Main*; and, one instance of class *ValueSpecificationActionActivation* having node as *ValueSpecificationAction1*. The object diagram in (V) – BS Fig. 3 shows the semantic domain according to the base semantics. In this case, the semantic domain is described by an object of type *Main* identified by *actOcc1* with two slots: *Main.ValueSpecification1* equals to *subactOcc1* (an occurrence of the action), and *Main.ValueSpecification1.variableX* equals to $1 \in \mathbb{Z}$ (the value of the *ObjectNode*). Moreover, (VI) – BS in Fig. 3 uses the CLIF syntax to represent the semantic domain exhibited in (V) – BS; it is one model (in the logic meaning) of the deduction process using the inference rules defined by the base semantics.

The base semantics formalizes the execution of an activity as defined in the example: occurrences of activities are instances of that, occurrences of actions are values for slots that the owning activity has, and object nodes assume values for slots from the owning activity (this definition is formalized in the next subsection). *ControlNodes* and control tokens are not embedded in semantic domain from the base semantics.

4.2 The Selected Subset

Fig. 4 shows the abstract syntax for the selected subset using set-theory (A), as well as, a class diagram (B). Further, (C) presents the grammar for this subset.

The sets, set operations and relations in (A) – upper left corner in Fig. 4 – define the relationship between the elements of the subset. Moreover, as discussed in the previous subsection, these relations are mapped to CLIF using unary and binary relations. In fact, this defines a mapping from the abstract syntax of the bUML into the embedded abstract syntax described by CLIF.

The class diagram (B) – upper right corner in Fig. 4 – presents the abstract syntax using the technique applied by fUML. It shows the selected subset, and indicates each meta-class and meta-relationship not formalized using orange color. These elements are also not embedded in the base semantics (OMG, 2012).

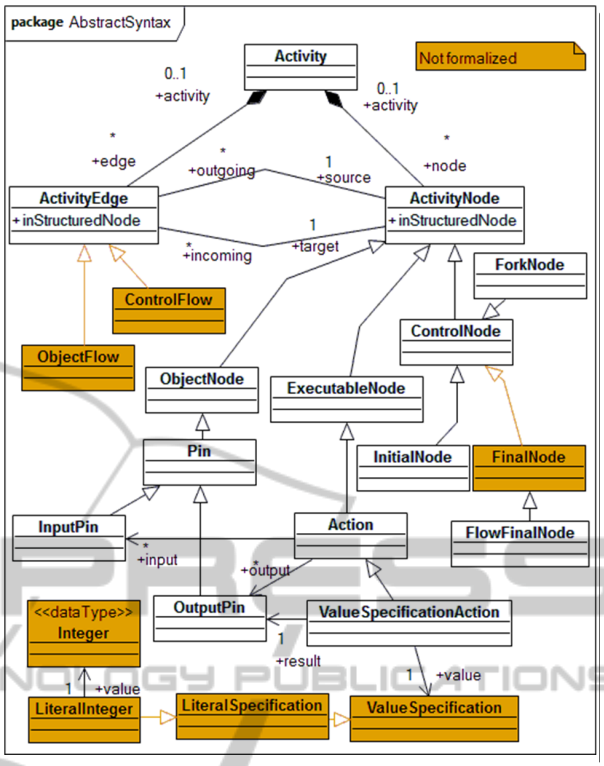
As discussed above, the base semantics does not define static semantics (OMG, 2012), e.g., it is not axiomatized that the sets *EN* (*ExecutableNodes*), *CN* (*ControlNodes*), and *ON* (*ObjectNodes*), subsets of the set *AN* (*ActivityNode*), should be disjoint ($EN \cap CN = \emptyset \wedge EN \cap ON = \emptyset \wedge CN \cap ON = \emptyset$).

The grammar (C) – lower left corner in Fig. 4 – defined using BNF (Backus-Naur Form) describes a text representation for activity diagrams. It is not used in the fUML, and the goal here is to allow a def-

(A)

c ∈ C set of	***Classifiers***	(buml:Classifier c)
z ∈ Z set of	***Integers***	
a ∈ A	A ⊆ C	(buml:Activity a)
an ∈ AN set of	***ActivityNodes***	(buml:ActivityNode an)
ae ∈ AE set of	***ActivityEdges***	(buml:ActivityEdge ae)
aan ∈ AAN	AAN ⊆ (AN ∪ AE) ⊑ A	(buml:activity an a)
cn ∈ CN	CN ⊆ AN	(buml:ControlNode cn)
en ∈ EN	EN⊆ AN	(buml:ExecutableNode en)
on ∈ ON	ON⊆ AN	(buml:ObjectNode on)
ac ∈ ACN	ACN ⊆ EN	(buml:Action ac)
fn ∈ FN	FN ⊆ CN	(buml:ForkNode fn)
in ∈ IN	IN ⊆ CN	(buml:InitialNode fn)
ffn ∈ FFN	FFN ⊆ CN	(buml:FlowFinalNode ffn)
owa ∈ OWA	OWA = A ⊑ (ACN ∪ ON)	
sn ∈ SN set of	***StructuredActivityNodes***	(SN ⊆ AN)= ∅
insn ∈ INSN	INSN = AN ⊑ SN	(buml:inStructuredNode an sn)
vsac ∈ VACN	VACN ⊆ AN	(buml:ValueSpecificationAction vsac)
pon ∈ PON	PON⊆ ON	(buml:Pin pon)
ipon ∈ IPON	IPON⊆ PON	(buml:InputPin ipon)
opon ∈ OPON	OPON⊆ PON	(buml:OutputPin opon)
aipin ∈ AIPON	AIPON = ∅ = ACN ⊑ IPON	(buml:input ac ipin)
aopin ∈ AOPON	AOPON = ACN ⊑ OPON	(buml:output ac opin)
sc ∈ SC	SC = AE ⊑ AN	(buml:source ae an)
tg ∈ TG	TG = AE ⊑ AN	(buml:target ae an)
inc ∈ INC	INC = AN ⊑ AE	(buml:incoming an ae)
out ∈ OUT	OUT = AN ⊑ AE	(buml:outgoing an ae)
rvsac ∈ RVACN	RVACN = VACN ⊑ OPON	(buml:result vsac opin)
vvsac ∈ VVACN	VVACN = VACN ⊑ VS	(buml:value vsac vs)
vs ∈ VS	***ValueSpecifications***	
lvs ∈ LVS	LVS ⊆ VS	
ilvs ∈ ILVS	ILVS ⊆ LVS	
vilvs ∈ VILVS	VILVS = ILVS ⊑z Z	(buml:value vs z)

(B)



(C)

activity ::= **empty | InitialNode → action | action**

action ::= **empty | Action | action → action, … | action → FlowFinalNode | Action O→ ForkNode**

Figure 4: Abstract syntax and grammar for the selected subset.

inition of the formal semantics (Subsection 4.4) using an operational semantics notation. It uses "→" as a symbol for *ControlFlow*, and "*O* →" as a symbol for *ObjectFlow*.

Concerning bUML, the selected subset does not use a *StructuredActivityNode* – as defined by A.3.3 Local Variable Declaration ((OMG, 2012); pp. 402) – to encompass the *ValueSpecificationActions*. However, this simplification still reassembles the local variable declaration in bUML that states: an object flow should connect the output pin from a *ValueSpecificationAction* to a *ForkNode*, which could be used for other actions ((OMG, 2012); pp. 402). Concerning Alf, the selected subset also applies a simplification without using *StructuredActivityNodes* to encompass sequences of commands (18.3 Block Statements; (OMG, 2013a); pp. 348). Therefore, the selected subset is able to describe variables in fUML, and sequences of statements declaring variables in Alf.

In conclusion, the selected subset is able to model $n(n \in \mathbb{N}_{>0})$ specifications of variables of the type *integer*, including the capacity for describing up to n concurrent specifications. However, it does neither cover loops, joins, nor calculations.

4.3 Rationale for Selection

Due to two respective reasons, a subset of the fUML, and consequently, axioms and inference rules defined in the base semantics are considered: (1) to show a complete example considering the semantics and the theorem proving approach for verification; (2) to demonstrate the use – due to the issues described in the appendix, it is impossible, at the moment, to use a complete version of the base semantics.

In contrast to the base semantics, the selected subset covers all the abstract syntax (see the appendix), and defined grammar. In fact, the selected subset uses *FlowFinalNode* instead of *ActivityFinalNode* because of the following proposition.

Proposition AFN: It is not possible to define formal semantics for the control node *ActivityFinalNode* with actual base semantics (OMG, 2012).

Proof: UML defines the *ActivityFinalNode* as "it stops all executing actions in the activity, and destroys all tokens in object nodes, except in the output activity parameter nodes" ((OMG, 2011); pp. 340). The present participle "executing" is used to qualify the word "actions", which means: given an action, it has started at a time $t - y$, the time is $t > t - y$, and it will finish at a time $t + x > t$, where $x, y \in \mathbb{N}_{>0}$.

Hence, to formalize *ActivityFinalNode*, time shall be defined formally. However, the base semantics does not formalize time (OMG, 2012), so it is not possible to define formal semantics for the control node *ActivityFinalNode* using actual base semantics (OMG, 2012). Although an alternative definition that could support the *ActivityFinalNode* formalization is the use of states (Grnniger et al., 2010), it would demand changes, not corrections, in the axioms defined by the base semantics. □

This issue is clearer in the presence of *ForkNode* without *JoinNode* (i.e., in the presence of concurrency without joining). In this case, it is not possible to know formally what activities are in execution (see Fig. 12.49; (OMG, 2011); pp. 341). Therefore, the selected subset uses *FlowFinalNode* that has an informal semantics (OMG, 2011) that does not depend on time, and this allows a simple formal definition.

4.4 Semantics

Given the abstract syntax, and the grammar, the current subsection explores the axioms and inference rules for the selected subset, which defines the semantic mapping. A file containing the definitions for the selected subset is available (Gerlinger Romero, 2013b).

Considering semantic domain and semantic functions for the selected subset (Fig. 5 – D), an object state is defined by an object identifier (obji), the classifier from this object (OBJIC, a semantic function), and the properties that the object has (PRV, a semantic function). The semantic function OBJIC is represented by the base semantics using a ternary relation *(form:classifies)* between domain, codomain, and a state identifier. The semantic function PRV is represented by the base semantics using a quaternary relation *(form:property-value)* between domain, codomain (property and value), and a state identifier. There are two types of properties: for *ExecutableNodes* and for *ObjectNodes*. The former has as codomain the property identifier, and one occurrence of execution (obji) of the action (acn) in a given instance of an activity (obji). The last one has as codomain the property identifier, and one integer value (z) retrieved by the relation $\sqsubseteq_z$ for the domain defined by an *ObjectNode* (on) in a given instance of an activity (obji). The set of all object states is the system state (SS), and the set-valued mapping *StateMapping* maps each system state into state identifiers (st).

As discussed in Subsection 3.2, the base semantics uses the embedding approach (Fikes et al., 2001) to axiomatize bUML. Accordingly, many inference rules are devoted to the formalization of the syntactical patterns. These syntactical patterns and the embedded abstract syntax are used as antecedent in the inference rules devoted to the semantic mapping. Hereon, each inference rule that supports semantic mapping for the selected subset is discussed. On the other hand, inference rules that support syntactical conditions are not shown, and when used in the semantic mapping, they appear in *italic*.

Concerning the inference rule [InitialNode → action], displayed in Fig. 5 (E), it checks the following syntactical pattern: an *InitialNode* with only one outgoing edge, which is connected to an *Action* (ac), and that *Action* does not have *InputPin*. If this syntactical pattern is recognized then the semantic mapping shall be applied: for all executions (obji) of an activity *(form:classifies)* that has the previous syntactical pattern, there exists an object state (for obji) where the action (ac) has run. Therefore, the obji acquired the value (objiac) for the property (obji $\sqsubseteq$ ac).

The inference rule [InitialNode → action] is presented using the base semantics style described by CLIF (center of E in Fig. 5), and using an operational semantics style (right of E in Fig. 5). The base semantics style is intended to be used directly by machines so a significant part of the antecedent is devoted to identify the syntactical pattern that this rule can be applied. The operational semantics notation avoids this making clear what syntactical pattern the rule supports, and in this sense, it is intended to express for humans the formal semantics for a given language (it is used by machines when a machine-readable notation is defined including the syntactical elements). One line shows the relationship between an antecedent (center) and a condition in the operational semantic notation (right). A second line presents the relationship between a consequent (center) and a premise in the operational semantic notation (right). The next rules use the same type of lines to clarify the relationship.

The next inference rule, [Action] shown in Fig. 5 (F), describes the semantic mapping for the syntactical pattern where an action has neither incoming edges nor *InputPins*, which means that the action shall be executed every time that owning activity runs (OMG, 2011). This interference rule uses a syntactical antecedent defined as a condition in the operational semantic notation, which is indicated with a dashed line in Fig. 5, and states that an action can run without an incoming control flow. The consequent is similar from the previous rule stating that the activity's execution (obji) acquired the value (objin) for the property (obji $\sqsubseteq$ n).

An action in the selected subset has only one concrete definition, the *ValueSpecificationAction*. There-

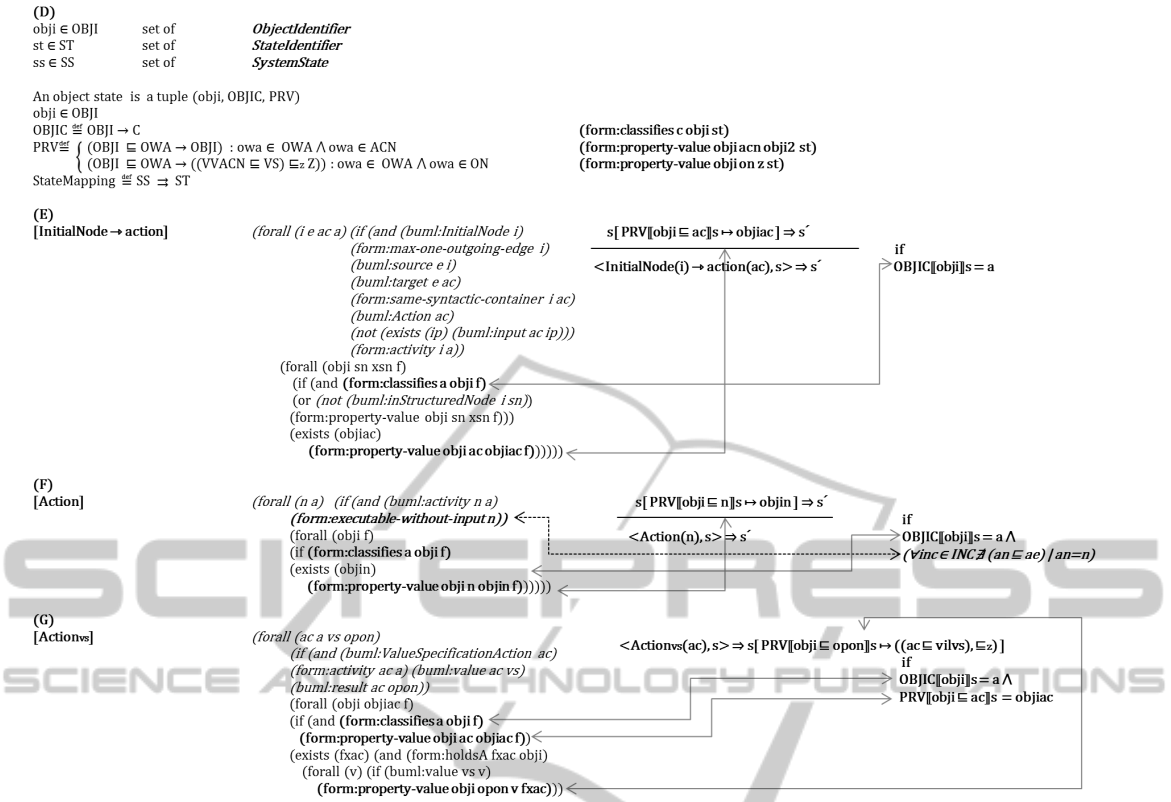


Figure 5: Semantics definition (part 1/2).

fore, the [Action$_{vs}$] shown in Fig. 5 (G) describes the inference rule for it, which defines that the integer value (v, considering just one) of the *ValueSpecification* is substituted on the *OutputPin* (opon, represented in the semantic domain as a property of the activity's execution). Moreover, the antecedent defines that it shall be evaluated only when the two conditions are satisfied: There is an execution for the activity *(form:classifies)*, and for the action *(form:property-value)*.

The next inference rule, [action → action,...] shown in Fig. 6 (H), illustrates that a control flow between actions is decomposed by evaluation of all possible flows (recursively, and without constraints about concurrency, e.g., interleaving). It is an unorthodox rule that is possible because the selected subset does not change the value from a previous defined property. This rule is defined for completeness of the operational semantics notation based on the previous defined grammar, whereas it does not exist in the base semantics style because it is covered for the (I) [action → action].

The rule (I) [action → action] covers control flows from one action to others, including possible many *ForkNodes* between them. These possible *ForkNodes* are recognized using the inference rule for this syntactical pattern *(form:flow-trans-fork-merge ac1 ac2)*. Therefore, the rule [action → action] checks if the activity has run, and if the source action has run. In this case, the target actions have run. It does not matter how many *ForkNodes* are between them, or how many targets have one source. Further, there is no notion of interleaving, sequence, or any type of constraint about concurrency in these evaluations. Indeed, fUML is not deterministic (Benyahia et al., 2010; Gerlinger Romero et al., 2013), hence multiple traces are accepted for the same embedded user axioms.

The rest of inference rules, namely [action → FlowFinalNode] and [Action O → ForkNode], are defined for completeness. The inference rule [action → FlowFinalNode] states that when an activity has run, an action has run, and the action is connected to a *FlowFinalNode*, then the state is not changed. The inference rule [Action O → ForkNode] states that an *ObjectNode* connected to a *ForkNode* does not change the state.

Considering the basic four building blocks (*InitialNode, ValueSpecificationAction, ForkNode* and *FlowFinalNode*), a permutation (selecting 1, 2, 3, and 4), where order is important and repetition is not allowed, generates 64 possibilities. From these, 12 follow the grammar defined in Fig. 4 – (B), which are

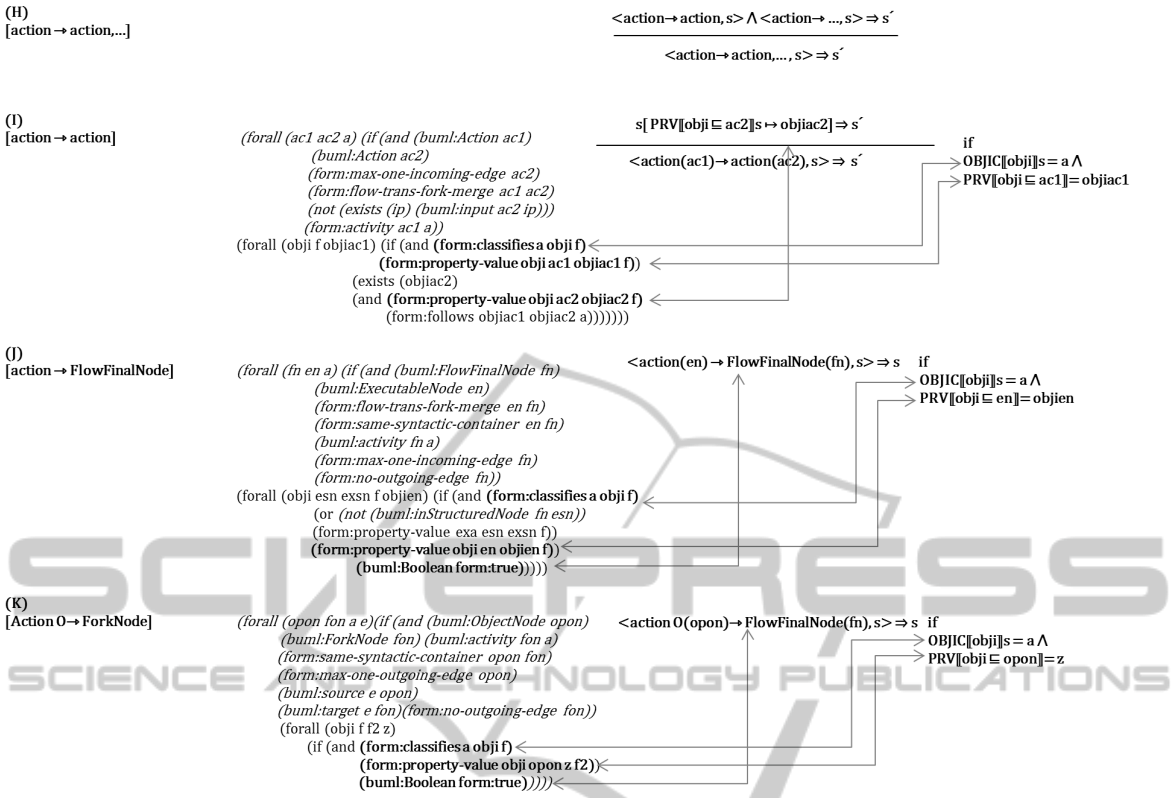


Figure 6: Semantics definition (part 2/2).

covered by the axioms and inference rules presented. Therefore, the axioms and inference rules are complete w.r.t. the allowed combinations defined by the grammar.

In summary, the axioms and inference rules refined from the base semantics (with corrections), and an illustration using the operational notation for the semantics definition are presented. The result is that the base semantics, defined using axiomatization of the abstract syntax (embedded), semantic domain, and, semantic mapping, can be related to operational semantics in general, an exception is concurrency (in the selected subset).

4.5 Formal Verification of Properties

Using the inference rules presented for the selected subset, it is possible to conduct proofs in one of the following two ways: (a) automatically, giving to an automated theorem prover (ATP) the embedded user axioms, the axioms and inference rules of the base semantics, and the user theorems; (b) interactively, using an interactive theorem prover that receives as input the axioms, inference rules and theorems; or (c) manually, e.g., using the operational notation.

Considering the example presented in Fig. 3 Subsection 4.1, one can formally verify that *for all* executions of activity *Main*, the property *variableX* has the value *1*. A possible formulation of this theorem called *activityMainAlwaysRunValueSpecification1AndValueIsForm1* is shown in Fig. 7. Informally, this theorem states: *for all* activity executions and states *(forall (exa f))*, *if* the execution *exa* and state *f* is from the activity *Main (if (form:classifies Main exa f))*, then there *exists* another state *f2 (exists (f2))* where the value *1* for the property *variableX* from execution *exa* is set *(form:property-value exa Main.ValueSpecificationAction1.variableX form:1 f2)*. Moreover, the theorem is described using CLIF with one extension from HETS (Mossakowski, 2013) to mark that the given text is a theorem (*%implied*).

Taking into account the simplicity of the example, the ATP eprover (Schulz, 2013) was applied to automatically perform the verification task, i.e., given all embedded user axioms (Fig. 3 (III) – BS), and the axioms and inference rules provided by the base semantics (Fig. 5 and 6), it shall find an application of inference rules to derive theorem *activityMainAlwaysRunValueSpecification1AndValueIsForm1*.

As formulas are described by CLIF and eprover does not support CLIF files (Schulz, 2013), HETS

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```
(cl-text activityMainAlwaysRunValueSpecification1AndValueIsForm1
        (forall (exa f)
                (if (form:classifies Main exa f)
                        (exists (f2)
                                (form:property-value exa Main.ValueSpecificationAction1.variableX form:1 f2)
                        )
                )
        )
)%implied
```

Figure 7: Theorem proved by the ATP eprover (Schulz, 2013).

(Mossakowski, 2013) was used to translate CLIF files into TPTP files (a format supported by eprover (Schulz, 2013)). The result of the translation performed by HETS was the input for eprover, which successfully proved the theorem in this case. The definitions and results of this proof, including the embedded user axioms and the UML model, are available (Gerlinger Romero, 2013b).

An alternative to perform this verification task is using the same set of formulas and an interactive theorem prover. The theorem prover can be launched by HETS (Mossakowski, 2013) after the translation from CLIF format to the supported format, and should be driven by the user interested in the verification. This option is well-suited for the verification tasks not so simple as the example presented above.

The last alternative (manual proof) demands huge manual effort, and can be performed stating a post condition for the activity and using the operational notation. For the example, the post condition can define that there should exist a state where the property *variableX* for the execution of the activity *Main* has the value *1*. Considering that there exists an execution for the activity (assumption), manual application of the sequence of inference rules defined using the operational notation ([Action] and [Action$_{vs}$]) leads to the defined post condition.

5 DISCUSSION

Concerning verification, there are two main approaches to perform formal verification: (a) model checking automatically and exhaustively traverses the reachable state space of a design and is limited by the state explosion problem (Jarraya et al., 2009; Kraemer and Herrmann, 2010); and (b) theorem proving which constructs a mathematical proof of a design's correctness and is usually limited by the high manual effort (Grnniger et al., 2010). The formal semantics considered in this paper supports both approaches, and in the current paper, the latter approach was explored and exemplified.

The base semantics uses CLIF to express syntactical patterns over the embedded abstract syntax, and to express the semantic mapping from instances of embedded abstract syntax to the semantic domain. The semantic domain of the execution model is not embedded in the base semantics. Nonetheless, the semantic domain in the base semantics has the features needed to define the semantic mappings (see Fig. 4) for the selected subset of bUML.

The base semantics is an axiomatization of the language defined by bUML, whereas it does not use the classical axiomatic semantics (Hoare, 1969). It can be related with operational semantics, as the article illustrates, while it does not apply SOS rules (Plotkin, 1981; Jarraya et al., 2009). Analyzing concurrency, rules [action $\rightarrow$ action,...] and [action $\rightarrow$ action], it is clear that axiomatization does not define all the operational implications. This absence of some operational details enables us to express the exact meaning of concurrency defined by UML (OMG, 2011). On the other hand, (Jarraya et al., 2009) applies interleaving using SOS. In the base semantics, the inference rules do not define the next element from the grammar to be processed, and instead it changes the state. An evaluator must analyze the next applicable rule considering the activity and the actual state, which is indeed, a characteristic of a deductive system.

Due to the limitations of the selected subset, the assertions ascribe particular values to variables (*ObjectNode*), instead of properties of the values and the relationship between them (Hoare, 1969). Further, the properties are verified as total correctness properties, due to the lack of loops, and advanced control structures.

There are three major limitations of the base semantics given by fUML that prevent its use: (1) fUML does not define semantics for time, intercommunication, and concurrency as well as the base semantics (OMG, 2012); (2) fUML does not define how the elements outside bUML (e.g., *LoopNode*) can be described by bUML – bUML is used to define an algorithm to interpret fUML (recall that the base semantics only covers bUML elements); and, (3) the lack of maturity of the base semantics (see Appendix).

6 CONCLUSIONS

The contributions of this work are: (1) it shows how the base semantics can support theorem proving for verification as well as its limitations, (2) it illustrates similarities and differences of the base semantics and an operational semantics, and (3) it helps in the maturation process of the specification itself (OMG, 2012) as well as in the motivation for more evaluations about this section of specification.

Evaluations of the base semantics are a necessity, e.g., the first syntactical defect described in the appendix was recognized in version 1.1 RTF from 2012 ((OMG, 2012); pp. 383). However, the same defect was detected in version FTF beta 2 from 2009 ((OMG, 2009); pp. 289). Further, fUML is a basic building block for future specifications of OMG. For example, Request for Proposal – Precise Semantics for Composite Structures (OMG, 2013b) states that new axioms must have explicit relationships with the base semantics, and must be consistent with it. Nevertheless, the base semantics is not consistent (see appendix) (OMG, 2012).

Although previous work has been done on the semantics of activities of UML, as discussed in Section 2, to the best of our knowledge, we introduce in this paper the first conceptual evaluation of the formal semantics (base semantics) defined in fUML. From the practical perspective, we show with a simple example how the base semantics can support formal verification (a requirement for safety-critical systems) through theorem proving. The initial results show that the base semantics, when mature, can play an important role in the formal verification of UML models, acting as a bridge between the modeling community and the formal semantics community.

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APPENDIX – BASE SEMANTICS

In this appendix, we present an extract from the issue report submitted (June, 30th, 2013) to OMG concerning the base semantics given by fUML ((OMG, 2012); pp. 351-398). In that report, 42 issues were found (Gerlinger Romero, 2013a), 5 of them were enhancement proposals, and 37 were defects. The main issues concerning defects were the following ones:

- The base semantics had a defect in Section 10.4.8.3, page 383. There was missing a *forall* construction, which lead to a syntax error.
- After having made the necessary corrections, a model finder (Schulz, 2013) was used to check if the fUML base semantics together with PSL (psl_outer_core; (NIST, 2013)) were consistent. However, it turned out that both together were inconsistent.
- A model finder (Schulz, 2013) was also used to check if the base semantics alone (without PSL) is consistent. It turned out that the fUML base semantics was not consistent.

The proposals sent to OMG were:

- A computer-readable version of the base semantics should be made available as a CLIF file.
- The base semantics should declare the PSL version used to define it.
- It should not define constraints for actions outside the bUML: *AcceptEventAction* and *ReadIsClassifiedObjectAction*.
- The specification should cover all *ActivityNodes* used in bUML. Thus, a declarative definition of *ActivityFinalNode* should be added because it is used in Annex A.3.1 and A.3.2, pages 401 and 402.
- Inference rules that are not used or not needed for completeness, should be removed.

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