Comparing the Effectiveness of Reasoning Formalisms for Partial Models

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ABSTRACT
Uncertainty is pervasive in Model-based Software Engineering. In previous work, we have proposed partial models as a way to explicate uncertainty during modeling. Using partial models, modelers can perform certain forms of reasoning, like checking properties, without the having to prematurely resolve uncertainty. In this paper, we present a strategy for encoding partial models into different reasoning formalisms and conduct an empirical study aimed to compare the effectiveness of these formalisms for checking properties of partial models.

1. INTRODUCTION
Modelers are routinely called upon to work with artifacts that contain varying degrees of uncertainty. However, existing modeling methodologies, tools, and libraries usually assume unambiguous artifacts. Modelers are thus often forced to act as if they were certain, artificially removing uncertainty from their artifacts. This carries the risk of making premature decisions, which can have significant effects on the quality of the produced software.

In [5], we introduced the idea of using partial models as first class artifacts to explicitly handle uncertainty by allowing the deferral of uncertainty resolution in model-based software development. A partial model is a model that represents a set of conventional models. In subsequent work, we’ve studied various aspects of this approach, such as property checking and diagnosis [6], refinement [15] and transformation [7]. In [17], we introduced MAVO partiality, as a way to explicate uncertainty using syntactic annotations. We introduced four kinds of such annotations:

• **May partiality**: annotating a model element with $M$ indicates that we are unsure about whether it should exist in the model or not,

• **Abs partiality**: annotating an element with $S$ indicates that we are unsure about whether it should actually be a collection of elements,

• **Var partiality**: annotating an element with $V$ indicates that we are unsure about whether it should actually be merged with other elements, and

• **OW partiality**: annotating the entire model with $INC$ indicates that we are unsure about whether it is complete.

Figure 1(a) shows a simple partial class diagram $M_1$. In addition to the class Vehicle, $M_1$ has several points of uncertainty, explicated with MAVO annotations: (a) We are uncertain whether we need to create separate classes for LandVehicle1es. (b) If we do that, we do not know how many such classes we may need to create. (c) We are not sure whether they should be subclasses of Vehicle. (d) We do not know where we should add the attribute numDoors in this hierarchy. Figure 1(b) shows a conventional model $m_1$ where all these points of uncertainty have been resolved. Such models that can result from systematically removing uncertainty from a MAVO model are called concretizations. In this example, LandVehicle has been refined to three classes Car, Truck and Motorcycle. The attribute numDoors has been assigned to the class Vehicle and thus the class Motorcycle does not inherit from Vehicle.

An important benefit of partial models is that we can check their properties without the need to remove uncertainty, thus facilitating decision deferral. For example, we might be interested in checking whether there can exist a refinement of $M_1$ that has cycles in the inheritance hierarchy.

In [17], we gave semantics to the MAVO annotations using First Order Logic (FOL) and demonstrated how they can be used for property checking using Alloy [11]. In this paper, we compare Alloy with three other reasoning formalisms, CSP [19], SMT [3] and ASP [12], aiming to determine which is most efficient for checking properties of partial models. We focus exclusively on the first three partiality types (May, Abs, Var). In the future, we intend to also study reasoning with OW, which is significantly harder, as it relaxes the closed world assumption. To facilitate meaningful comparison, we created an encoding of MAVO in Relational Algebra that can be readily translated into the different modeling formalisms. Using this encoding, we set up a series of experiments using randomly generated MAVO models.

The rest of the paper is structured as follows: Section 2 gives necessary background on MAVO models and the reasoning formalisms. Section 3 introduces the relational encoding of MAVO. Section 4 describes the experiments for comparing the reasoning formalisms. We discuss related work in Section 5 and conclude in Section 6.

2. BACKGROUND

MAVO models. In this paper, we consider models expressed as typed, directed graphs. The model $M_1$ in Figure 1(a) is shown in
its abstract syntax as a typed graph $G_{M_1}$ in Figure 1(c). Classes and attributes are represented in $G_{M_1}$ as typed nodes; inheritance and attribute ownership as typed edges. A typed graph’s nodes and edges are called its elements. $G_{M_1}$ conforms to the type graph $G_{CD}$, shown in Figure 1(d), that corresponds to the signature of a very simple UML Class diagram metamodel. $G_{CD}$ specifies that there exist Classes and Attributes, that one Class can inherit another, and that Classes can own Attributes.

A MA VO model is simply a typed graph whose elements can be decorated with the MA VO annotations. Semantically, a MA VO model represents a set of conventional models (its concretizations). We consider a non-annotated model to be a MA VO model that represents a set containing exactly one concretization. In Figure 1(c), MA VO annotations are shown in black circles. For example, the attribute numDoors is owned by the class X annotated with v, indicating that it can be merged with some other Class node.

In Section 1, we introduced the idea that a MA VO model can be refined [17] to conventional models, based on the MA VO annotations of its elements. This is done by refining the individual elements of the MA VO model (“MA VO elements”) to elements in the concretization (“instance elements”), according to the definitions of the different MA VO annotations. For example, in the concretization $m_1$, shown in Figure 1(b), the instance elements Car, Truck and Motorcycle refine the s-annotated MA VO element LandVehicle of $M_1$.

**Reasoning formalisms.** In this section, we briefly introduce the four reasoning formalisms that we study in this paper.

Alloy [11] allows users to create First Order Logic specifications expressed in relational logic. Using the Alloy Analyzer tool, these specifications are grounded within an explicit bounded scope to create a CNF representation. Properties can be expressed as assertions and an off-the-shelf SAT solver, such as Minisat [4], is used to attempt to disprove the assertions by finding counterexamples.

**Constraint Satisfaction Problems (CSP)** operate over a finite set of variables and a finite set of constraints over them. The CSP solver attempts to find values of all variables so that all constraints are satisfied. For our investigation, we used Minizinc [13], a medium-level constraint modeling language and solver designed for specifying constrained optimization and decision problems over integers and real numbers.

**Satisfiability Modulo Theory (SMT)** solvers combine the standard constraint satisfaction search with richer theories, such as linear arithmetic, bitvectors, arrays, etc. [3]. The standardized input language SMT-LIB2 [2] is often used for modeling the problem. For our investigation, we used Z3, an SMT solver and theorem prover developed at Microsoft Research [3].

**Answer Set Programming (ASP)** [1] combines a rich declarative input language based on logic programming with negation-as-failure. Solutions to an ASP program are minimal sets of atoms that are supported by and consistent with the program. Modern ASP solvers are based on a modified DPLL procedure or compile the input program into CNF and use an off-the-shelf SAT solver. For our investigation, we used the solver Clasp [9] with the program grounder GrinGo [8]. GrinGo accepts rules with variables, arithmetic, sets, and cardinality constraints.

3. **ENCODING MA VO**

We introduced FOL semantics for MA VO in [17]. Here, we present an encoding of MAVO models in Relational Algebra (RA), a formalism typically used in the field of database management systems (DBMSs) [18]. This encoding is intended to be used as a specification that can be readily implemented in the same way in all four reasoning formalisms that we study in this paper.

Intuitively, our encoding represents MA VO elements as relations whose content is constrained according to their MA VO annotations. We present it by illustrating the steps required to encode the example the partial model $M_1$ shown in Figure 1(a).

For each type in the MA VO model’s type graph, we create an instantiation relation which associates MA VO elements of that type with their refining instance elements in the concretization. All instantiation relations for $M_1$ are shown in Figure 1(b). For example, consider the type CLASS from the type graph $G_{CD}$ in Figure 1(d). Its corresponding instantiation relation, CLASS, relates MA VO elements in $M_1$ with the instance elements in $m_1$, shown in Figure 1(b), that refine them. For example, LandVehicle is refined by the instance elements Car, Truck, and Motorcycle.

Every instantiation relation like CLASS has two columns, one for MA VO elements and one for instance elements. We keep track of all elements of the MA VO model in a special relation called Constants. The instance elements are declared in a separate set of relations called universe relations.

The Constants relation has an entry for every MA VO element, keeping track of its name, its type and its MA VO annotations. In our example, the relation Constants for $M_1$ is:

<table>
<thead>
<tr>
<th>name</th>
<th>type</th>
<th>isM</th>
<th>isS</th>
<th>isV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Class</td>
<td>True</td>
<td>False</td>
<td>True</td>
</tr>
<tr>
<td>LandVehicle</td>
<td>Class</td>
<td>False</td>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Class</td>
<td>True</td>
<td>False</td>
<td>True</td>
</tr>
<tr>
<td>numDoors</td>
<td>Attribute</td>
<td>False</td>
<td>False</td>
<td>True</td>
</tr>
<tr>
<td>gl</td>
<td>Inherits</td>
<td>True</td>
<td>False</td>
<td>True</td>
</tr>
<tr>
<td>cl</td>
<td>Owns</td>
<td>False</td>
<td>False</td>
<td>True</td>
</tr>
</tbody>
</table>

We create one universe relation for each type of element. When a MA VO model is concretized, the universe relations are popu-
lrelated with instance elements. The universe relations for \( M_1 \) are shown in Figure 2(a). In our example, they have been populated with the instance elements of the concretization \( m_1 \). E.g., the relation \( \text{Inherits}_\text{Univ} \) contains two inheritance instance elements, \( g/1 \) and \( g/2 \), as both \text{Car} and \text{Truck} inherit from \text{Vehicle} in \( m_1 \).

We define bound to be the maximum number of instance elements that can be associated with some MAVO element in an instantiation relation. Choosing an appropriate bound is necessary for most solvers because they typically ground the encoding to some finite representation. The choice of the bound can have significant implications: for example, when the bound is 2, \( m_1 \) is not a valid concretization of \( M_1 \) because \text{LandVehicle} is associated with three instance variables in the relation \text{CLASS}.

The relational-algebraic definitions of the instantiation relations of \( M_1 \) are shown in lines 3-7 of Figure 3. The instantiation relation for each type is defined as the Cartesian product of its universe with the subset of the elements of that type in the relation \text{Constants}. The result is stripped of the additional metadata columns from \text{Constants} using projection, to only keep a column for MAVO elements and one for instance elements. In general, in instantiation relations, a MAVO element can be associated with any number of instance elements. Additionally, different MAVO elements may be associated with the same instance element. In our example, in \text{CLASS}, \text{LandVehicle} is associated with three instance elements (\text{Car}, \text{Truck} and \text{Motorcycle}), while \text{Vehicle} and \( X \) are both associated with the instance element \text{Vehicle}.

The possible ways that MAVO elements can be associated with instance elements are constrained by the presence or absence of MAVO annotations. In an instantiation relation, MAVO elements that aren’t annotated with \( S \) cannot be associated with more than one instance element. In our example, only the MAVO elements \text{LandVehicle} and \text{gl} are \( S \)-annotated, so all others are associated with at most one instance element. The relational-algebraic definitions of the \( S \) constraints for \( M_1 \) are in lines 13-17 of Figure 3. There is one constraint for each MAVO element that does not have an \( S \) annotation. For example, the constraint for the element \text{Vehicle} selects the records containing it from its type’s instantiation relation (\text{CLASS}) and checks whether the selection contains more than one record.

In an instantiation relation, MAVO elements that are not annotated with \( M \) must be associated with at least one instance element (which is true in our example). Yet \text{gl} is associated with only two inheritance instance elements: there exists one instance of \text{LandVehicle} (the element \text{Motorcycle}) that does not inherit \text{Vehicle}. The relational-algebraic definitions of the \( M \) constraints for \( M_1 \) are given in lines 8-12 of Figure 3. For example, the constraint for the element \text{Vehicle} selects the records containing it from its type’s instantiation relation (\text{CLASS}) and checks whether the selection is empty.

Pairs of MAVO elements of the same type where both don’t have the annotation \( V \), e.g., \text{Vehicle} and \text{LandVehicle}, cannot share instance elements. However, \text{Vehicle} does share an instance element with the \( V \)-annotated element \( X \). The relational-algebraic definitions of the \( V \) constraints for \( M_1 \) are given in lines 18-23. For example, the constraint for the element \text{Vehicle} creates two selections: one by selecting from \text{CLASS} all instance elements refining \text{Vehicle} and one by selecting from \text{CLASS} all instance elements refining other non-\( V \)-annotated elements. The constraint then uses natural join to check whether these two selections intersect.

In addition to the universe and instantiation relations, and the MAVO constraints, we also define other relations and constraints, to ensure that concretizations are structurally well-formed graphs. For every \( edge \) type, we create two graph relations, one for the source and one for the target. The graph relations for \( M_3 \) are shown in Figure 2(c). E.g., for the type \text{Owns} from the type graph \( G_{CD} \) in Figure 1(d), we have the relations \text{Owns}_\text{Source} and \text{Owns}_\text{Target}. The former says that the source node of \text{cl} is the class \text{Vehicle}; the latter that its target node is the attribute \text{numDoors}.

The relational-algebraic definitions of the graph relations of \( M_1 \) are shown in lines 24-28 of Figure 3. According to \( G_{CD} \), the source node of any instance element of type \text{Owns} must be of type \text{Class} and its target of type \text{Attribute}. Therefore, the source graph relation for \text{Owns} is defined as the Cartesian product of the universe relation of \text{Owns} and that of \text{Class}. The target graph relation is defined similarly. For clarity, the columns of each Cartesian product are renamed to “left” and “right”, where “left” always refers to the \text{Owns} element and “right” to its source or target node.

The well-formedness of concretizations is ensured by constraints over graph relations. We create one graph constraint for each MAVO edge element requiring that (a) if an instance edge exists, its source
and target instance nodes also exist, and (b) the edge’s type is respected. For example, the existence of the endpoints Vehicle and numDoors also exist, and (b) the edge’s type is respected.

Implementation details. The RA encoding that we present here is designed to function as an intermediate representation between the FOL semantics of MAVO, presented in [17], and reasoning formalisms such as Alloy, CSP, SMT, and ASP. More efficient encodings, that take advantage of the intricacies of each of these formalisms such as Alloy, CSP, SMT, and ASP. More efficient encodings, that take advantage of the intricacies of each of these formalisms, such as Alloy, CSP, SMT, and ASP. More efficient encodings, that take advantage of the intricacies of each of these formalisms, such as Alloy, CSP, SMT, and ASP. More efficient encodings, that take advantage of the intricacies of each of these formalisms, such as Alloy, CSP, SMT, and ASP.

In the Alloy encoding, we implement relations as Alloy uninterpreted boolean functions. A function implementing a relation returns True for tuples that belong to the relation, and False otherwise. MAVO constraints are implemented in quantified logic over the truth tables of the functions. Unlike the other formalisms, SMT does not require an explicit bound because the solver is able to efficiently handle infinite types using abstraction.

In the ASP encoding, we use a set of program rules to generate ASP atoms representing a bounded number of instance elements. Another set of program rules generates ASP atoms to represent the relations on these instance variables. Finally, a set of program rules eliminates solutions that do not correspond to a valid instantiation given the MAVO constraints.

4. EXPERIMENTS
To study the effectiveness of the four reasoning formalisms for checking properties of MAVO models, we conducted a series of experiments. To simplify our investigation, we did not consider the OW partiality type, focusing instead on the other three: May, Set and Var.

Figure 3: Relational encoding of the MAVO model $M_2$ shown in Figure 1(a).
Each generated model was automatically translated into each reasoning formalism and checked for five properties. The properties, shown in Figure 4, were inspired from the structural well-formedness constraints of the models in our three reference case studies. The result of the run is determined as follows [6]: a property is True (False) for a MAVO model iff it is True (False) for all its concretizations. If the property is True for some concretizations and False for others, then the result of checking the property is Maybe, meaning that it depends on how the MAVO model is going to be refined. Therefore, in order to check a property, we have to run the solver twice: once to find a concretization where the property is True and once where it is False.

Each experiment was repeated for three different values of bounds, set to 2, 4 or 6. We ran each experiment five times and recorded the average for each datapoint. We set cut-off values for runtime and memory consumption to 10 minutes and five GB of RAM, respectively. The experiments were run on an Ubuntu 10.04 LTS 64-bit machine with two quad-core Intel E5355 CPUs with 2.66 GHz and 28GB of RAM. Our recorded observations are available online at http://www.cs.toronto.edu/~pooya/modevva12.html.

**Results.** In our experiments, 8.2% of property checks turned out to be True, 18.4% False, and 32.3% Maybe. An additional 41.1% of checks was inconclusive because of time-outs. We present the (averaged) results in Figures 5(a-c), for bounds 2, 4 and 6, respectively. Each chart tracks the changes in runtime for each modeling formalism as the reasoning problems become harder with increasing size. The horizontal axis captures the model size (S, M, L, XL); the vertical axis records the timing score for each solver. The score is calculated as the percentage of the total allocated time (120 sec.) that was unused after the solver completed all five property checks. A solver that times out for all 5 properties gets a score of 0%. The runtime also reflects the solver’s performance with respect to memory consumption (exceeding the memory limit causes disk usage thus slowing the solver down). In general, a higher score means that the solver needed less time and less memory to complete.

In the figures, SMT is represented by a solid black line and is consistently above roughly 80% and (as expected) is unaffected by bound. CSP, indicated by an orange dotted line with rhombuses, consistently scores below 20% for anything except S models. Alloy (blue dotted line with rectangles) performs well for S, M and L models and small bounds, but rapidly deteriorates with larger models and increasing the bound. ASP is indicated by a green dotted line with triangles. Its performance follows that of SMT, but dete-
Our observations indicate that with increasing bound and model size, SMT generally performs better than the other formalisms. The only case where SMT does not score the best is for models in the L category and bound 2, where it scores 86.92%, compared to 94.83% from Alloy. For the easiest problem (S models and bound 2), all formalisms performed very well, scoring close to 100%. In general, the performance of ASP was comparable to that of SMT, except for models in the XL category. For all bounds and for all categories except XL, the average difference between the score of ASP and that of SMT was 4.42%. However, for XL models their average difference was 41.61%.

The worst score that we observed for SMT was 77.65% for models in the XL category. To further study the limitations of using SMT for reasoning, we conducted an additional experiment. We incrementally increased the size of the problem, extrapolating linearly from the four model size categories in Table 1. We found that SMT’s score dropped to 41% for models in the category with (175,200) elements. In other words, doubling the size of the model almost halved the score.

We thus concluded that SMT is the most efficient of the four solvers for checking properties of MAVO models. SMT is unaffected by increases in bound; more importantly, it is designed for reasoning with specifications at a higher level of abstraction, without needing the potentially expensive translation and/or grounding phase required by the other formalisms. These characteristics allow the SMT solver to consistently outperform other formalisms.

Threats to Validity. There are three main threats to the validity of this experimental study: (a) the use of randomly generated MAVO models, (b) the fairness of comparison between the different formalisms vis-à-vis the efficiency of the encodings, and (c) our choice of specific reasoning engines. To mitigate the first threat, we tuned the generator to create random models with realistic graph density and frequency of MAVO annotations. Additionally, we fixed these properties to values found in existing MAVO case studies.

With regard to the second threat, it is clear that the perfect comparison would require using the most efficient encoding in each formalism which is impossible to do. Instead, we opted to create a common encoding that is directly implementable in each formalism. This way we leveled the playing field, enabling meaningful comparisons.

To address the third threat, we used solvers that won recent competitions in their respective communities (Z3, Clasp, Alloy with Minisat). To our best knowledge, there has been no recent CSP competition. We thus chose MiniZinc because of its convenient modeling language.

5. RELATED WORK

In [6], we experimentally studied the effectiveness of reasoning (property checking and diagnosis) for partial models that only contain May partiality (these are called May models). For this, we used an intuitive encoding of May models directly as propositional expressions which was used as input to a SAT solver. In [15, 7], we used Alloy [11] to verify properties of transformations of MAVO models. In this paper, we expand the scope of our study by considering more types of partiality, as well as by considering different verification tools.

Software product line (SPL) analysis has connections to our work: they express sets of models in a manner similar to May models. In [14], Pohl et. al. do a study to compare the use of SAT, CSP and Binary Decision Diagrams (BDDs) to check properties of feature models. They conclude that BDD-based solvers – the approach we did not examine – have the best performance. Their results are not comparable to ours since they check properties of the entire set of concretizations such as “do they exist a concretization?” whereas we check properties that could hold for each concretization separately (see Figure 4). However, we are inspired to conduct experiments with BDD-based solvers in the future.

6. CONCLUSION

We presented a comparison of four reasoning formalisms (Alloy, CSP, SMT and ASP) with regard to their effectiveness in checking properties of MAVO models. In order to have meaningful comparisons, we introduced an encoding of MAVO, in relational algebra, that can be readily translated into each of these formalisms. We carried out the comparison by running experiments where we used the four reasoning formalisms to check five properties on randomly generated models. Our investigation indicates that, in general, the most efficient formalism is SMT, as it scales better for increasingly hard problems. In the future, we intend to expand the scope of our study to include the OW partiality, as well as to incorporate more complex problems, such as those requiring transitive closure.

7. REFERENCES