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A Tool for Domain-Independent Model Mutation

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Abstract

Mutation is a systematic technique to create variants of a seed artefact by means of mutation operators. It has many applications in computer science, like software testing, automatic exercise generation and design space exploration. Typically, mutation frameworks are developed ad-hoc by implementing mutation operators and their application strategies from scratch, using general-purpose programming languages. However, this is costly and error-prone.

To improve this situation, we propose `WODEL`: a domain-specific language and tool for model-based mutation that is independent of the domain meta-model. `WODEL` enables the rapid development and application of model mutations. It provides built-in advanced functionalities like automatic generation of seed models, and static and dynamic metrics of operator coverage and applicability. It offers extension points, e.g., to post-process mutants and describe domain-specific equivalence criteria. As an example, we illustrate the usage of `WODEL` for the mutation of security policies, and present an empirical evaluation of its expressiveness.

Keywords: Model-driven engineering, domain-specific languages, model mutation, mutation footprint, model synthesis

1. Introduction

This paper presents `WODEL`, an extensible software tool for model mutation that consists of: (1) an *editor* to define mutation operators and their application policies, featuring code completion and code validation; (2) a *compiler* of

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5 WODEL programs into executable Java code implementing the defined operators;
 (3) metrics for *mutation footprints* which provide information about the static
 coverage of a meta-model by a mutation program, as well as about the effects
 of the dynamic execution of a mutation program on a given set of models; (4)
 a *seed model synthesizer* to automatically generate seed models ensuring the
 10 application of the defined operators; and (5) an *extensibility mechanism* that
 allows pipelining external applications to WODEL programs.

The rest of this paper is organized as follows. First, Section 2 identifies some
 limitations of existing mutation frameworks to define mutation-based applica-
 tions. Then, Section 3 describes the architecture and main functionalities of
 15 WODEL, and Section 4 gives details of its implementation. Section 5 illustrates
 WODEL using an example in the domain of security policies [1]. Finally, Sec-
 tion 6 evaluates the expressiveness of our proposal, and Section 7 ends with the
 conclusions and lines of future work.

2. Motivation and background

20 Model mutation is the process of generating variants (i.e., mutants) of a seed
 model by the application of a set of mutation operators. Mutation is essential
 to applications like mutation testing [2, 3], where a program is modified and
 then used to assess the quality of a test suite; automated generation of mod-
 elling exercises [4], where variations of a correct solution model are presented to
 25 students, who must identify the injected errors; model-driven design space ex-
 ploration [5, 6], where the goal is to heuristically find a model optimizing some
 property, and the model population is generated by mutation; and synthesis of
 a diversity of test models which are generated by mutating some given seeds [7].

Although there are some frameworks for model mutation, their scope is
 30 limited to either a particular language (e.g., logic formulae [8]) or application
 domain (e.g., testing [9, 10]). Moreover, mutation operators must be defined
 using general-purpose programming languages not tailored to the definition and
 creation of mutants. Hence, developing domain-specific applications that rely
 on mutation (liked the abovementioned ones) becomes costly and error-prone,
 35 because existing tools do not facilitate the creation and analysis of mutation
 operators for arbitrary languages and application domains.

In order to fill this gap, we propose a model-based mutation approach where
 the artefact to be mutated is represented as a model conformant to a domain
 meta-model, and the mutation operators are defined using a domain-specific
 40 language called WODEL. WODEL provides high-level primitives to simplify the def-
 inition of mutation operators and their application strategies, and it supplies
 some built-in services to facilitate the generation of mutants, like a registry
 of applied mutations, the ability to detect duplicated or malformed mutants,
 debugging support, and synthesis of seed models that exercise the operators.
 45 The framework provides handy integration with external applications through
 a compilation into a general-purpose programming language. Moreover, it is ex-
 tensible with post-processing actions that can use the generated mutant models,
 like mutation testing or exercise generation [4].

3. Software framework

Figure 1 shows the modular, component-based architecture of our mutation framework. The typical workflow is as follows. First, since our approach is domain-independent, the user needs to describe the domain concepts by means of a domain meta-model (label 1 in the figure). For example, in order to mutate automata, the user should provide a meta-model including the concepts of state, transition and alphabet symbol, as well as how they relate to each other.

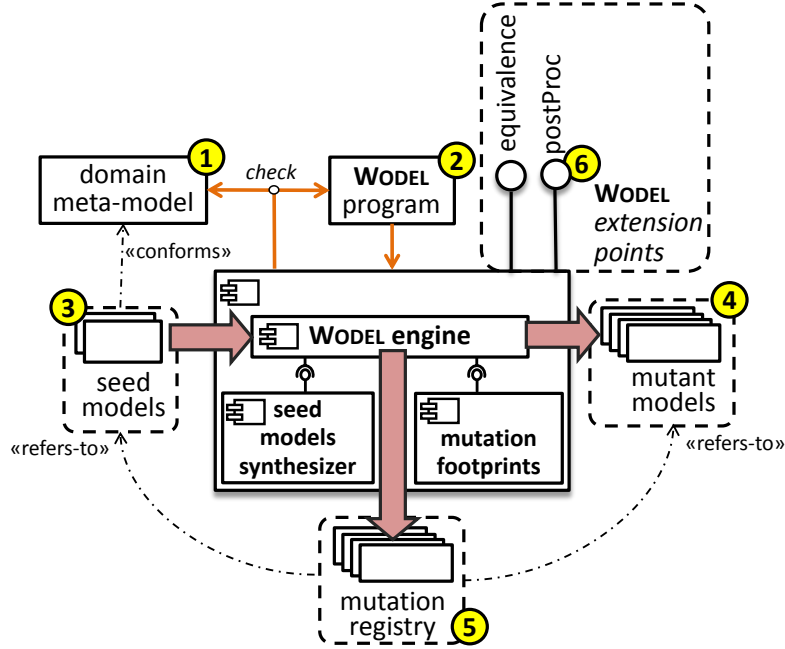


Figure 1: Architecture of the WODEL development environment

Next, the user defines the desired mutation operators and their execution details, like how many times each mutation operator should be applied, or the mutation execution order. We call this specification a WODEL program (label 2). WODEL is meta-model independent, which means that it can be used to define mutation operators for arbitrary meta-models. Nonetheless, WODEL programs must refer to a domain meta-model to allow type checking – to assure the program only refers to valid meta-model types and features – and to ensure the resulting mutants are valid.

Once created, a WODEL program can be applied to seed models conforming to the given domain meta-model (label 3). For convenience (e.g., to exercise the defined operators and assess their correct implementation), we provide a *seed model synthesizer* that is able to generate seed models to which all mutation operators in the program are applicable.

The execution of a WODEL program produces mutant models from the seed

70 models (label 4), as well as a mutation registry keeping trace of the modified
 elements and applied mutation operators (label 5). In addition, the tool offers
 two extension points (label 6) to further customize WODEL for a domain or appli-
 cation. The first extension point permits specifying domain-specific equivalence
 criteria to avoid the generation of duplicate mutants. The second extension
 75 point allows registering application-specific post-processors for the generated
 mutants, e.g., for mutation-based testing or automated exercise generation [4].

Next, we describe the functionalities that WODEL offers to facilitate the defini-
 tion and generation of mutants:

- 80 • WODEL provides nine mutation primitives for object creation and deletion,
 reference redirection, attribute modification, object retyping, and shallow
 and deep object cloning, among others. The primitives can define a range
 between m and M , and can be combined into composite mutations with
 transactional semantics. The mutation candidate objects can be selected
 85 according to different strategies, like randomly, based on some property
 value, or to all objects satisfying certain property.
- 90 • The engine verifies that each generated mutant is a valid model (i.e., it
 conforms to the domain meta-model and satisfies its integrity constraints).
 Non-conformant mutants are discarded, in which case, the engine attempts
 to generate another mutant up to a configurable maximum number of re-
 tries. WODEL programs can include OCL invariants [11] that any produced
 mutant is enforced to satisfy.
- 95 • When generating the mutants, the engine takes care of assigning an ap-
 propriate value to any mandatory attribute or reference not initialized
 by the WODEL program. Similarly, new objects are automatically placed
 in a suitable container, if no explicit container is stated. This way, pro-
 grams become more compact, and the likelihood to obtain valid mutants
 is higher.
- 100 • WODEL includes a mechanism to identify and avoid duplicate mutants. En-
 suring uniqueness of mutants is useful in some applications, like the auto-
 mated generation of exercises [4] or mutation testing. By default, mutant
 equivalence is syntactic, but users can provide their own equivalence cri-
 teria (e.g., behavioural) through an extension point.
- 105 • The execution of a WODEL program produces a registry of applied muta-
 tions and objects affected by them (label 5 in Figure 1). This registry
 can be used to replicate the mutation process, or for application-specific
 purposes. For example, we have used it to synthesize a natural language
 description of the mutations, in order to include it in automatically gener-
 ated exercises [4]. The registry is stored as a model, and can be compacted
 110 to eliminate mutations that cancel each other (e.g., a mutation that creates
 an object, and another that deletes it).

- An optional post-processing step can be used to generate domain-specific artefacts tailored to particular applications (label 6 in Figure 1), like mutation testing or exercise generation [4].
- 115 • WODEL provides some metrics that help in analysing the behaviour of mutation programs. On the one hand, the static footprint of a WODEL program identifies the meta-model classes and features touched by the program, and the kind of changes it performs (creation, deletion or modification). This information is computed statically, and is useful to identify immutable types or undesired mutation side effects. On the other hand, WODEL programs are stochastic, as each mutation operator can be configured to be applied a random number of times at random locations. To ascertain the actual operators applied to build a mutant, the dynamic footprint of the program execution can be inspected. There are two types of dynamic footprints: net (i.e., net effect of the program execution calculated by differencing the seed model and the mutant) and debugging (i.e., detailed enumeration of applied operators). This information can help to locate program errors by identifying parts of the seed model that were not mutated as expected. The footprints are available via dedicated Eclipse views with drill-down tables showing the information organized either by meta-model element or by mutation operator, and where cells use different colours to easily distinguish between creation, modification and deletion actions.
- 120
- 125
- 130
- 135 • To facilitate the evaluation of WODEL programs and exercise their operators, the IDE permits the automatic synthesis of seed models ensuring that all instructions in the program will be applicable to the models (if any such models exist within a given search bound).

4. Implementation

140 WODEL is available as an Eclipse plugin. It includes an Xtext¹ editor for WODEL programs which features syntax highlighting, automatic code completion, and type-checking of programs against the specified domain meta-model to ensure only valid meta-model types and features are used. The underlying modelling technology is the Eclipse Modelling Framework (EMF) [12], the de-facto standard for modelling within Eclipse nowadays.

145 WODEL programs are compiled into Java using an Xtend² code generator. The produced Java code, which is in charge of creating the mutants from the seed models, can be transparently executed from the IDE, or in a separate standalone application. Being able to execute WODEL programs outside the IDE may be needed by some applications, and is the reason why we opted for a compiled approach.

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¹<http://www.eclipse.org/Xtext/>

²<http://www.eclipse.org/xtend/>

The seed model synthesizer relies on model finding, a technique based on constraint solving over models [13]. In particular, the synthesizer produces a description of the domain meta-model and its OCL integrity constraints, enriched with additional OCL invariants derived from the `WODEL` program. The invariants express the requirements that a seed model must fulfil to enable the application of each mutation operator in the program. For example, the `WODEL` instruction `remove one ElementType` requires the seed model to contain an instance of `ElementType` to ensure the instruction is applicable, which is encoded as the OCL invariant `ElementType.allInstances()->size() > 0`. Then, the enriched meta-model is fed into the USE Validator [14] model finder, which searches for models that are valid instances of the domain meta-model and satisfy the invariants. Users can customize the search by providing a search scope (minimum and maximum number of objects in the seed models), additional model requirements expressed with OCL, or a seed EMF model for the search.

Figure 2 is a screenshot of `WODEL` which shows its editor (label 1), the Java code generated from a `WODEL` program (label 2), a domain meta-model and some seed models (label 3), several mutants generated from the seed models (label 4), and the static and dynamic footprints of the program (label 5). The different artefacts in the screenshot correspond to an example in the domain of security policies, which we will develop in the next section.

As the figure shows, the static footprint view counts the number of explicit and implicit creations (C, IC), modifications (M, IM) and deletions (D, ID) of each meta-model class and feature (upper-left view), or performed by each mutation operator (lower-left view). The cells corresponding to classes aggregate the actions performed on the class and its features. For instance, the cell for the explicit creation of class `Rule` contains 1c 2f because the program contains one explicit creation of `Rule` objects and two explicit creations of its features. The first row of the tables displays the average class coverage for each type of action. For example, the explicit creation percentage is 14% because the program explicitly creates 1 out of the 7 classes in the domain meta-model.

The dynamic footprints to the right (net and debug) have columns stating the number of elements actually created (C), modified (M) and deleted (D) by the execution of the `WODEL` program over two seed models (`LibraryOrBAC` and `LibraryRBAC`), and the effects of each mutation operator on the models.

5. Example

Next, we illustrate `WODEL` with an example in the context of mutation testing for security policies. Here, the goal is measuring the quality of a set of test cases by injecting errors in the artefact under test (a security policy), and then checking whether the test cases detect the injected errors. We have chosen this application scenario because it is concise, but still, it will allow demonstrating all features of our tool.

We base the example in the work of Mouelhi and collaborators [1]. They pro-

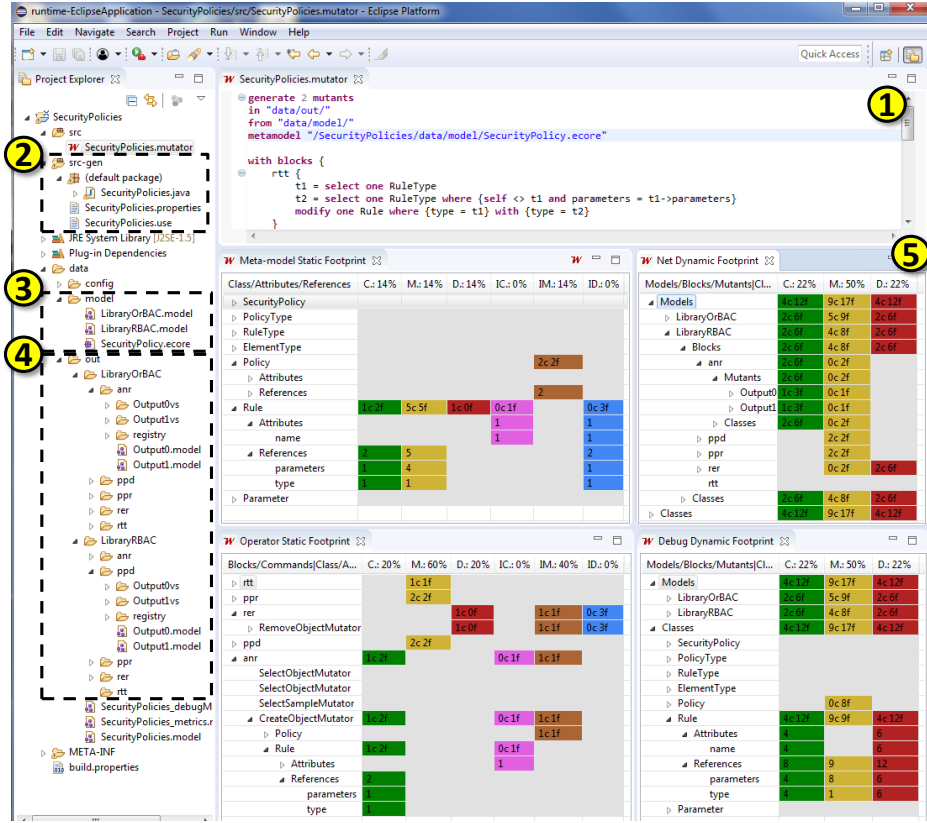


Figure 2: The WODEL IDE in action

pose a meta-model to represent both access control languages – like RBAC³ and OrBAC⁴ – and security policies expressed with them. Hence, this meta-model contains classes like RuleType or PolicyType to represent access control languages, and classes like Rule or Policy to specify security policies. In addition, the authors define five mutation operators for security policies expressed with this meta-model, so that the operators are independent of the concrete access control language (i.e., RBAC or OrBAC). Table 1 shows their proposed generic mutation operators.

We can use WODEL to define the operators in this table. As an example, Listing 1 shows the WODEL program that implements the PPD mutation operator. This mutation replaces one rule parameter with one of the parameter descendants. Line 1 states that mutants are to be generated in folder *out*, from the seed models in folder *models*. The number of mutants generated from each

³Role-Based Access Control

⁴Organization-Based Access Control

Table 1: Mutation operators for security policies (from [1]).

RTT:	Selects two rule types with the same parameter types. Then modifies the type of a rule whose type is the first selected rule type with the second rule type
PPR:	Replaces a rule parameter with a different one (of same type)
ANR:	Creates a new rule using a selected rule type
RER:	Removes a rule
PPD:	Replaces a parameter on a rule with one of its descending parameters (using the children reference)

seed is configurable. Line 2 indicates the meta-model the seed models conform to. Lines 5–10 define the PPD mutation operator. In particular, line 6 selects one Rule having at least one parameter with descendants, and stores the rule in variable *r*. Since *Rule.parameters* is a collection, *Rule.parameters.children* collects the children of each *Parameter* object in reference *parameters*, and flattens the result in a single collection. Then, line 7 selects one parameter of rule *r* with non-empty children, and line 8 selects one descendant of the selected parameter. By using the function closure, which iteratively collects all reachable elements through a reference, we consider both direct and indirect descendants of the parameter. Line 9 removes the parameter selected in line 7 from rule *r*, and adds the parameter descendant selected in line 8 to *r*. In line 10, the range [1..2] allows applying the operator once or twice at random.

```

1 generate mutants in "out/" from "models/"
2 metamodel "http://SecurityPolicy.com"
3
4 with commands {
5   PPD = [
6     r = select one Rule where {parameters.children <> null}
7     p = select one Parameter in r.parameters where {children <> null}
8     c = select one Parameter in closure(p.children)
9     modify r with {parameters -= p, parameters += c}
10  ] [1..2]
11 }

```

Listing 1: WODEL program encoding the PPD mutation operator

Figure 3 shows an application of this operator to a seed model. The operator selects one rule having a parameter with children (*Personnel*), and replaces such a parameter by one of its descendants (*Secretary*). The objects selected in lines 6–8 of the listing (*r*, *p*, *c*) are marked in the figure.

The screenshot in Figure 2 corresponds to this example. The editor (label 1) contains the definition of all operators in Table 1, although only RTT is visible. The static footprint (label 5) shows that the operators do not mutate classes *PolicyType*, *RuleType* and *ElementType*, which is sensible as those classes are used to model the access control language. However, the footprint also uncovers that no object of type *Parameter* is created, modified or deleted, and its feature *Parameter.children* is neither mutated. Since this class is used to define security policies, this suggests the need for further mutation operators dealing with *Parameters* and their hierarchies.

In the same screenshot, the dynamic footprint shows that the RTT operator

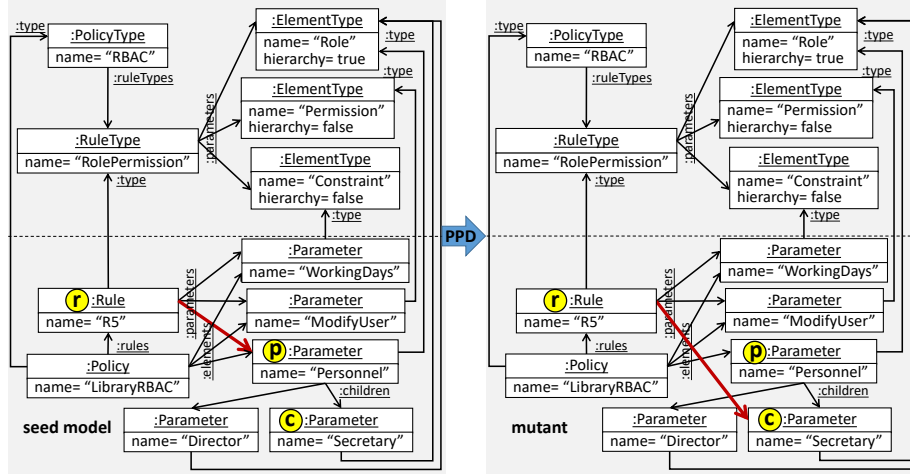


Figure 3: Example of application of the PPD mutation to a security policy in RBAC

could not be applied on the RBAC seed model (LibraryRBAC). If we inspect the RBAC language definition, we realise that RBAC only defines two rule types with different parameter types. Since RTT requires a rule pair with same parameters, it cannot be applied to any security model expressed with RBAC. This can be confirmed by generating additional seed models for RBAC using the seed model synthesizer.

Altogether, this example illustrates how WODEL simplifies the definition of mutation operators (e.g., the definition of the PPD operator using Kermeta requires three times more LOCs [1]), and how it permits analysing the defined operators using footprints and seed generation.

6. Empirical results

To evaluate the expressiveness and usefulness of WODEL, we have used it to define and analyse sets of mutation operators proposed in the literature. We have implemented mutations for automata [4, 15] with the purpose of automated exercise generation; and mutations for probabilistic automata [16], class diagrams [17], BPEL [18] and security policies [1] for mutation testing. The purpose of this experiment is to assess the expressiveness of WODEL to deal with realistic mutation operators, and to show the usefulness of its metrics to evaluate sets of mutation operators.

Table 2 summarizes the results. The columns show the number of implemented mutation operators (we show in parenthesis the number of operators proposed in the original publication); the meta-model size in classes; the mutation percentage including both explicit and implicit Creation, Modification, and Deletion actions; and the percentage of non-mutated concrete classes (column unmodified). The encoding of the operators is available at <http://gomezabajo>.

Table 2: Evaluating sets of mutation operators.

	#mutation operators	#mm classes	static footprint			
			C	M	D	unmodified
Automata [4]	10 (10)	4	50%	75%	50%	25%
Automata [15]	4 (4)	4	25%	75%	0%	25%
Prob. automata [16]	4 (4)	4	25%	75%	0%	25%
Class diagrams [17]	50 (50)	49	47%	37%	82%	16%
BPEL [18]	18 (26)	133	13%	20%	44%	50%
Sec. policies [1]	5 (5)	7	14%	28%	14%	57%

github.io/Wodel/samples.html. The metrics shown in the table have been statically computed by WODEL.

270 The column `unmodified` reveals none of these works provide full mutation coverage with respect to the domain meta-model, i.e., they do not mutate all meta-model classes and features. The first two sets of automata mutations [4, 15], which are used to automate exercise generation, do not mutate the class `Symbol`. Hence, the alphabet of the automata cannot get changed, although this would
275 be useful to generate more variety of exercises.

The mutations for probabilistic automata in [16] provide even less coverage: they do not change the alphabet either, there are no deletion mutations, and there are creation mutations only for `Transitions`. Hence, these mutations yield mutants with same alphabet as the seed, same states, and emulate faults by
280 changing transition targets, their probabilities, the initial state, or adding extra transitions. However, for mutation testing, it would be interesting to add new states, or to delete transitions re-adjusting the siblings' probabilities.

The class diagram mutations in [17] are quite complete, as indicated by the low percentage of unmodified elements (16%).

285 The BPEL mutations in [18] have low meta-model coverage, as they do not mutate 50% of the meta-model concrete classes. The reason for this low coverage is that the mutations aim at modelling programming mistakes when implementing WSBPEL 2.0 compositions using graphical tools. From the proposed 26 mutations, we were able to encode 18. The remaining 8 were related to
290 expressions, and we could not define them because the meta-model represents expressions as external objects.

The mutations for security policies [1] have low coverage, but this is because they do not mutate the classes to specify access control languages, but only those to define security policies, which is sensible. Anyhow, we miss being able
295 to mutate `Parameters` and their hierarchical organization, which would be useful for testing.

Altogether, we could specify most mutations (91/99) in the analysed works using WODEL, demonstrating its expressiveness. The footprints WODEL provides helped in identifying omissions for automata, security policies and BPEL, but
300 confirmed a reasonable coverage for class diagrams.

7. Conclusions and future work

Mutation has many applications in computer science, but there is currently a lack of general approaches to define mutation operators. WODEL fills this gap using a model-based approach to mutation. It has the advantage of being domain-independent, enabling the rapid development of mutation operators using a dedicated domain-specific language. The tool offers advanced functionality for the automatic generation of seed models, and to calculate the static and dynamic footprints of WODEL programs. We have used our tool to define collections of mutation operators defined in the literature, identifying limitations in those sets and showing the usefulness of footprints in practice.

In the future, we plan to extend WODEL with OCL helpers, as well as with smart synthesis of mutation operators that maximize the coverage of the static footprint. We plan to work on further static analysis techniques, e.g., to detect operator conflicts and dependencies. Finally, we are working on a dedicated WODEL post-processor for mutation testing.

Acknowledgements

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Nr.	(executable) Software metadata description	
S1	Current software version	1.1
S2	Permanent link to executables of this version	http://gomezabajo.github.io/Wodel/
S3	Legal Software License	EPL-1.0 License
S4	Computing platform/Operating System	Microsoft Windows 7 64-bit or later, Linux
S5	Installation requirements & dependencies	Eclipse
S6	If available, link to user manual - if formally published include a reference to the publication in the reference list	http://gomezabajo.github.io/Wodel/
S7	Support email for questions	pablo.gomeza@uam.es

Table 3: Software metadata

Current code version

Nr.	Code metadata description	
C1	Current code version	1.1
C2	Permanent link to code/repository used of this code version	https://github.com/gomezabajo/Wodel
C3	Legal Code License	EPL-1.0 License
C4	Code versioning system used	git
C5	Software code languages, tools, and services used	Eclipse Modelling Tools Oxygen Release (4.7.1a), EMF 2.13.0, Java 1.8, Xtext 2.8.4, Xtend 2.8.4, Sirius 5.0.2, EMF Compare 3.3.2, OCL Examples and Editors SDK 3.4.5, USE ModelValidator 4.2.0
C6	Compilation requirements, operating environments & dependencies	Microsoft Windows 7 64-bit or later, Linux
C7	If available Link to developer documentation/manual	http://gomezabajo.github.io/Wodel/
C8	Support email for questions	pablo.gomeza@uam.es

Table 4: Code metadata