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An MDE performance testing framework based on random model generation

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ABSTRACT

The scalability of model-related operations (e.g., model transformations), when they are to be applied in industrial model-driven engineering, becomes an important issue. However, there is a lack of an automated performance testing framework for those operations, since the existing ones for ordinary programs are ill-suited. Such a framework is required to provide the function of creating and organizing test cases, and the ability of generating test input of large size automatically, because large scale models are not widely available, making it hard to test the performance and coverage of those operations without any bias. This paper proposes a performance testing framework, integrated with a random model generation algorithm, for model-related operations. The framework, based on a test model, can be used to specify and arrange test cases into test suites. And the model generation algorithm can generate a random model correctly and efficiently, according to the metamodel and user-defined constraints. Finally, we present two case studies, one experiment in randomness, and two experiments in generation efficiency to evaluate the framework and algorithm. Results show that the framework is competent to support performance testing of model-related operations, and the algorithm is *random* and *efficient* enough to generate test data for performance testing.

1. Introduction

Model-Driven Engineering (MDE) employs models to drive the development and the maintenance of software systems. The model, the core artifact in MDE, serves as the abstraction of the software system. Then, a number of *model-related operations*, such as model refactoring, model synchronization, model composition, and model-to-code transformation, are applied to models to automate the development process.

Due to the increasing complexity of the system, software models are becoming larger and more complicated than they were ever before, consequently, consume much more processing time. How to query, analyze, convert, and merge large models efficiently has become a key factor. Especially in such an era of *Big Data*, handling big models extracted from volumes of codes or structural documents within a reasonable time is an essential ability for those model-related operations.

For example, when *runtime model* is applied to maintaining a running system Song et al. (2011), a bidirectional model transformation is used to keep the runtime architecture model, which reflects the logical structure of the running system, and the runtime system model, which reflects the actual structure, consistent. Developers can modify the runtime architecture model, and the changes will be propagated by the transformation to the runtime system model to affect the actual system. However, if the transformation could not be done efficiently, the system may have entered another state before the changes are produced by the transformation. Consequently, a system failure may come about when the changes are being applied, since the changes may not be valid anymore in the new system state.

Hence, the performance of a model-related operation in MDE must be systematically evaluated before it is put into practice. Evaluating the performance enables us to find out the limitations and bottlenecks of those operations for further improvement. However, there is a lack of tool support that can manage and facilitate performance testing of those operations. Besides, most of those operations are declarative, and are based on the type system of Meta Object Facility (MOF, Object Management Group (2011)) or Ecore (an industrial implementation of MOF)[1] and Object Constraint

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[1] Eclipse Modeling Project: https://www.eclipse.org/modeling/emf/ (Sep. 20, 2015).

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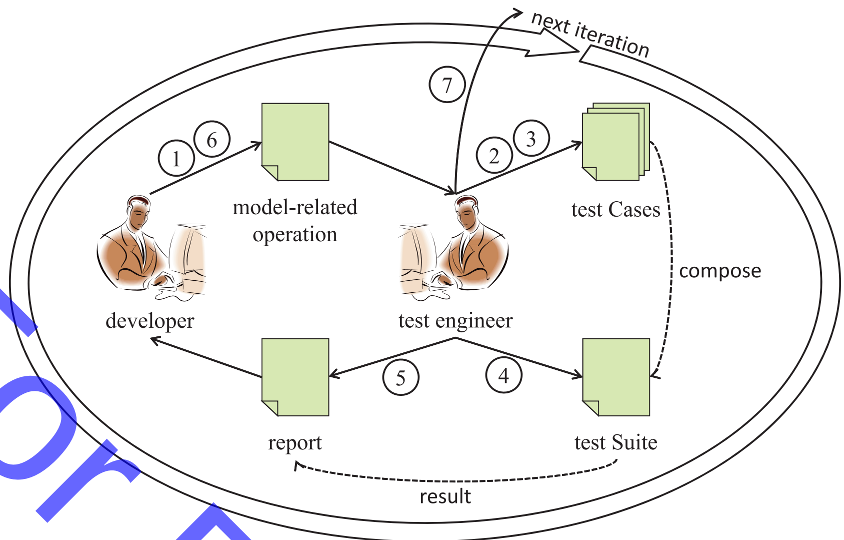


Fig. 1. Iterative testing process of model-related operations.

Language (OCL, Object Management Group (2012)) rather than common programming languages. Due to those particularities, current performance testing tools for ordinary application systems are not directly applicable to them.

One of the essential functions that must be provided by a performance testing tool is to generate large-size test data (i.e., the input model) automatically, since manually establishing an input model is an error-prone and time-consuming procedure. The basic requirements of generating models used in performance testing are listed as follows: (1) *Correct*: The generated model should conform to the syntactic constraints. (2) *Efficient*: The input data should be generated efficiently in order to test the efficiency of a model transformation. (3) *Randomized*: The model should be generated in a stochastic way to capture the average performance of an operation. (4) *Configurable*: The generation process should be configurable, e.g., users must be able to control the amount of elements.

This paper proposes a testing framework that meets the basic requirements of performance testing for model-related operations. It provides the abilities of defining, organizing, and performing the test cases. The paper also proposes a randomized model generation approach, which has been integrated into the framework to facilitate the test input generation. In this approach, all the elements and relationships are produced *randomly* within a reasonable amount of time. In addition, during this process, all metamodel-implied syntactic constraints and some semantic constraints are taken into account to assure the *correctness* property. It also supports some user-defined constraints guiding the generation process for better *configurability*. Two case studies are presented in this paper to demonstrate how to employ this framework to evaluate the performance of model-related operations. Besides, the results of three experiments are also introduced to show that our approach is *efficient* in generating a large correct model *randomly*.

The following paper is structured: Section 2 presents our performance testing framework; Section 3 defines some basic concepts and constraints for random model generation; Section 4 proposes a randomized and efficient model generation algorithm integrated into the testing framework, used to produce test data automatically; Section 5 presents two case studies and three experiments to demonstrate the feasibility and the usability of our framework, and to evaluate the randomness and the efficiency of our model generation algorithm; Section 6 discusses some issues about our approach; Section 7 compares our approach with other related work; at last, conclusion and future work are presented.

2. Performance test framework

2.1. Framework overview

Testing the model-related operation, which is actually a program, becomes more and more important in model-driven engineering. There are two basic roles involved in this iterative task: developers and test engineers. Fig. 1 shows how they interact with others.

1. The developer submits their model-related operation (i.e., SUT) to the test engineer.
2. The test engineer writes a test plan and creates initial test cases.
3. For each test case, test engineer must construct a valid test input data.
4. The test engineer selects some test cases and arranges them into a test suite, and performs it.
5. The test engineer collects the results and reports them to the developer.
6. The developer refines the program and then resubmits it to the test engineer.
7. The test engineer performs the test suite again to evaluate how much the operation has been improved, and then he or she may append some new test cases to the test suite to test it incrementally and iteratively.

Hence, our framework, aiming at such a testing process, is required to own the following abilities: (1) defining and storing the test cases; (2) constructing the test data automatically; (3) arranging and performing test cases; (4) monitoring and analyzing the execution of a test case; (5) collecting and reporting results.

The architecture of our test framework is presented in Fig. 2. We have to emphasize that this framework is extensible,

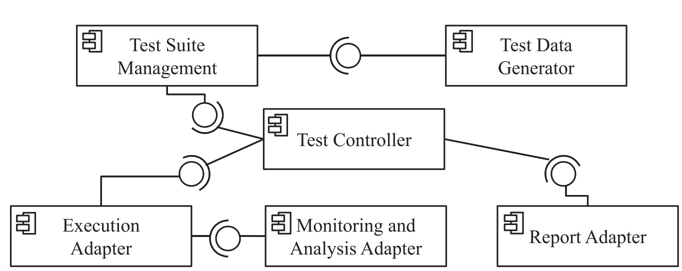
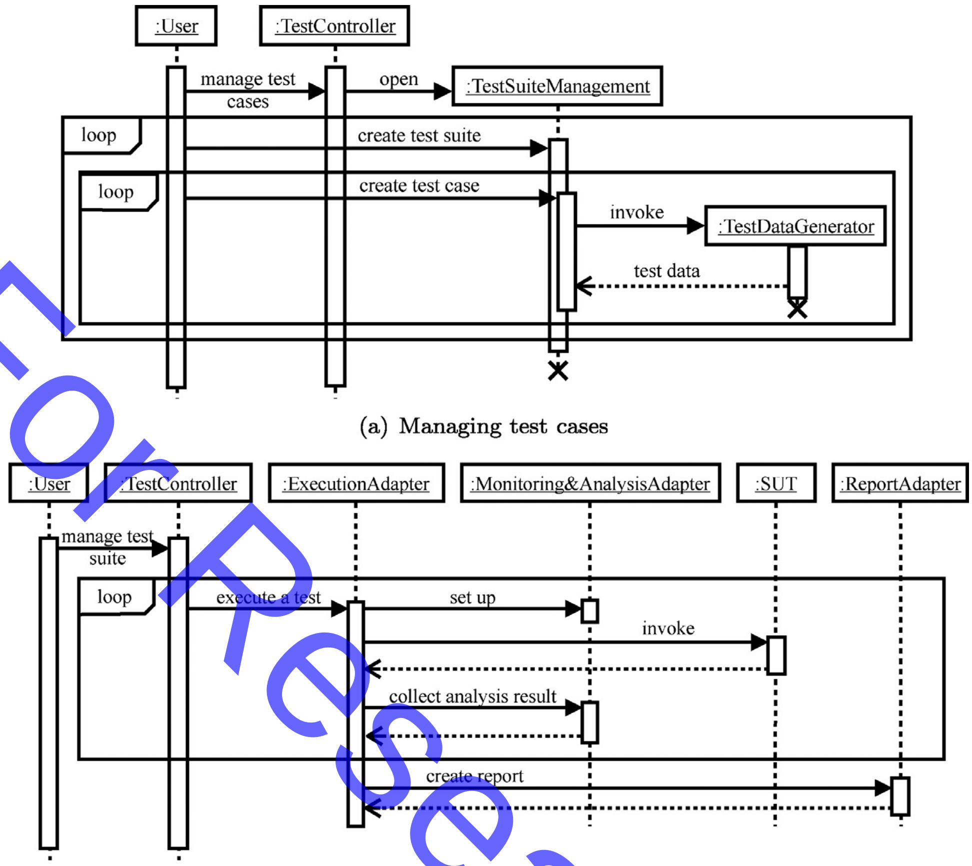


Fig. 2. Architecture of our test framework.



(a) Managing test cases

(b) Performing test cases

Fig. 3. Interactions among components.

because it includes some replaceable components. There are six components:

- *Test controller* serves as a control center, which is in charge of organizing the performance testing process. It requires three interfaces: 1) test case and test suite management interface; 2) test execution interface; 3) result report interface. When the user wants to manage test cases and suites, the controller will invoke the test suite management interface to serve the required functions (as shown in Fig. 3(a)). When a single test case or a test suite is to be performed, the controller will invoke the test execution interface to launch the SUT and to collect the results (as shown in Fig. 3(b)). Note that to perform a test suite the execution interface will be requested once for each test case included in the test suite. After collecting the test results, the controller will finally invoke the report interface to present them.
- *Test suite management*, an implementation of test case and test suite management interface, provides the function of specifying cases and managing test suites based on the *Test Model* for model-related operations, which will be discussed in Section 2.2. This component supports regression testing. It invokes a generator interface to produce test data when creating a test case (Fig. 3(a)).
- *Test data generator*, which implements the generator interface, can be used to generate a large model randomly. This component is replaceable so that test engineers can employ other generation strategies to produce test data. However, this paper proposes a randomized model generation algorithm for this specific task, which is discussed in Sections 3 and 4.
- *Execution adapter* realizes the test execution interface. It can be reckoned as a bridge to the concrete execution engine on which the SUT can be executed. Model-related operations may not be implemented using general-propose programming languages, such as Java and C++. Their execution might rely on various kinds of execution engines. For example, a model comparison using EMF (Eclipse Modeling Framework) Compare [2] can be performed directly on JVM, while an ATL[3] transformation could only be executed on ATL Virtual Machine. This component is responsible for communicating with execution engines so as to invoke the SUT. It also requires a monitoring and analysis interface to trace the runtime information and to analyze the performance of SUT. We have implemented a default execution adapter, which can execute an SUT according to the launch configuration[4] on Eclipse platform. It prepares the input data based on a test case and then invokes the launch configuration to perform the SUT.
- *Monitoring and analysis adapter*, which implements a performance analysis interface, is invoked by *Execution Adapter* to monitor and analyze the performance of the SUT. A default adapter has been realized. It treats the SUT as a black box and calculates the span between the starting and the finishing time. It is also possible to realize a more fine-grained monitor for a particular kind of operations, for example, a monitor that can record the execution time of each rule in an ATL

[2] EMF Compare Project: https://www.eclipse.org/emf/compare/.
[3] ATL Transformation Language: https://www.eclipse.org/atl/.
[4] A program could be executed on Eclipse platform after a launch configuration has been established for it.

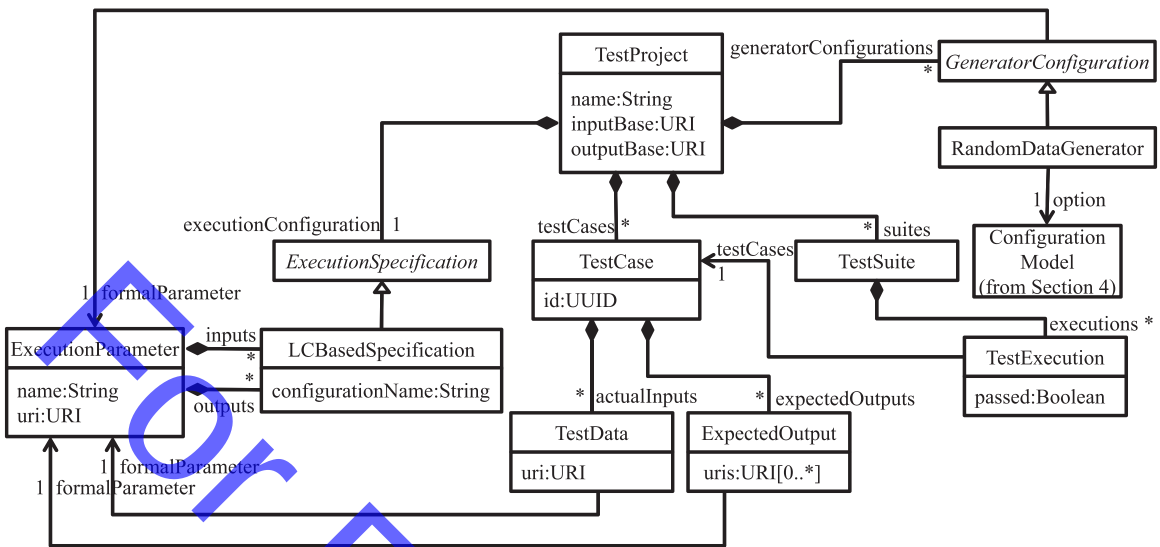


Fig. 4. Definition of *Test Model*.

transformation would be conducive to find out the performance bottleneck.

- *Report adapter* is responsible for displaying the test result. The default implementation prints the results onto the console. It can be substituted for another one that can present results diagrammatically.

2.2. Test model

The foundation of this framework is the *Test Model*, a domain-specific model of testing model-related operations. It is used to define and manage test cases. The test controller can interpret a test model and perform tests automatically. Fig. 4 shows its definition.

TestProject is the root class of this domain model. When developers submit a new SUT, test engineers would create an instance of *TestProject*. It has three attributes: *name* of this project, *inputBase*, and *outputBase*. *inputBase* and *outputBase*, whose types are *URI* (i.e., universal resource identifier), point to the folders containing all the input model files and the expected output model files respectively.

To test the SUT, we must execute it. As mentioned above, those model-related operations may only be executed on their own engines, and our framework must be able to invoke those engines. *ExecutionSpecification* in Fig. 4 is used to specify the essential information needed by *ExecutionAdapter* in Fig. 2 to configure an engine. Each subclass of *ExecutionSpecification* corresponds to a particular *ExecutionAdapter* which is responsible for interpreting the information contained in the configuration. *LCBasedSpecification*, a subclass of *ExecutionSpecification* depicted in Fig. 4, is used by the default execution adapter mentioned in Section 2.1, where the first two characters *LC* stand for launch configuration. Its attribute *configurationName* is the name of a launch configuration stored in Eclipse platform. The default execution adapter will invoke the configuration whose name is equal to this value.

If the program associated with the launch configuration has inputs from files, it is needed to specify where the inputs are read by creating instances of *ExecutionParameter* and linking them to the *LCBasedSpecification* element with *inputs* relationships. The *name* of *ExecutionParameter* is a unique identifier of the input file, and *uri* is the file path where the program will import data. It is also possible to use *ExecutionParameter* to define output files of the program by connecting it to *ExecutionParameter* element with *outputs* relationship, when the output is used for result analysis.

A *TestProject* contains a number of *TestCases*. Without losing generality, a *TestCase* consists of an *id*, a set of actual inputs, and a set of expected outputs.

Actual input of a *TestCase* is specified by *TestData*. Its *uri* specifies a file that serves as input of the SUT. It also refers to an *ExecutionParameter* that serves as the formal parameter. When the *TestCase* is performed, the file indicated by *uri* of *TestData* will be copied to the location specified by the *uri* of the corresponding formal parameter so that the SUT can read it.

Expected output of a *TestCase* is denoted by *ExpectedOutput*. It contains a set of *URIs* each of which denotes a file containing the expected output. If the SUT can produce one of those results, we think it is correct. Note that although comparing the actual output with the expected output is not necessary for performance testing, embedding this concept in the test model enables further functional testing using our framework.

Each *TestProject* can include a number of *TestSuites*. Each *TestSuite* consists of a set of *TestExecutions*, which represents one execution of a *TestCase*. It has a Boolean attribute named *passed* indicating if the SUT passes through the *TestCase*. In the mode of regression test, our framework will copy all the *TestCases* referred by the previously created *TestSuite* to the newly established one so that those *TestCases* could be tested again.

When constructing a *TestCase*, we must be able to generate the input data automatically. To do so, we can employ a test data generator. *GeneratorConfiguration* specifies the configuration information of a certain test data generator. Each subclass of *GeneratorConfiguration* corresponds to an implementation of a data generator, which can generate a test input according to the configuration. *RandomDataGenerator* is a subclass of *GeneratorConfiguration* that works with the default test data generator in our framework. It is related to a generation *ConfigurationModel* which will be defined in Section 4.

3. Definitions and generation constraints

As mentioned in the previous section, one must be able to construct the test input automatically when creating a test case in our framework. To propose the model generation approach, this section defines some basic concepts and constraints used in this process.

3.1. Definitions

Definition 1 (Metamodel)**.** Without losing generality, a metamodel $\mathcal{M}$ can be formally defined as follows:

$$\mathcal{M} = (T, H, A, R, C, assoc, mult, \prec) \quad (1)$$

In the definition,

- T is the set of *classes*. Each class represents a type of elements.
- H is the set of the abstract classes, and $H \subset T$.
- A is the set of attributes. Each attribute a in A can be defined as a signature a: $t_c \rightarrow d$, where a is the identifier, $t_c \in T$, and d is a primitive data type. The symbol I_d denotes all the possible values whose types conform to d.
- R is the set of *references* among types. Each reference represents a type of relationships among elements.
- C is the set of containment references, and $C \subseteq R$.
- *assoc* is a function $R \rightarrow T^2$. It maps each reference $r \in R$ to a pair $\langle src, tar \rangle$ of classes, which indicates the source and the target of r. For simplicity, if $assoc(r) = \langle s, t \rangle$, $r.source \equiv s$ and $r.target \equiv t$.
- *mult* is a function $R \rightarrow \mathbf{N}^2 \times \mathbf{N}^2$, which specifies the multiplicity of each reference, where $\mathbf{N}$ signifies all non-negative integers (including $+\infty$). For a reference $r \in R$, *ls* and *us* determine the lower and the upper bound of the source end of r respectively, and *lt* and *ut* determine the lower and the upper bound of the target end of r respectively, where $(\langle ls, us \rangle, \langle lt, ut \rangle) = mult(r)$.
- $\prec$, denoting the generalization hierarchy, is a partial order on T. If $c_1 \prec c_2$, c_1 is a child (descendant) class of c_2. If c_1, c_2, $c_1 = c_2 \vee c_1 \prec c_2$.

For any class c,

$$\sqcup_c \equiv \{p | c \preceq p\}, \quad \sqcap_c \equiv \{p | p \preceq c\}$$

Definition 2 (Model)**.** A *model* M conforming to a metamodel $\mathcal{M}$ can be formally defined as follows:

$$M = (E, L, type_E, type_L) \quad (2)$$

where E is the element set, L is the relationship set, $type_E$ is a function $E \rightarrow T$ mapping an element to its type, and $type_L$ is a function $L \rightarrow R$ mapping a relationship to its type.

Supposing $M = (E, L, type_E, type_L)$, we have the following definitions:

- For an element e and a class t, $e \in_t M \Leftrightarrow e \in E \wedge type_E(e) = t$.
- For an element e and a set of class X, $e \in {}_X M \Leftrightarrow e \in E \wedge type_E(e) \in X$.
- For an element $e \in_{t_c} M$ and an attribute a: $t_c \rightarrow d$, $a(e)$ is the value of the attribute a of e.
- For two elements a and b, and a reference r, we say $\langle a, b \rangle \in {}_r M$ iff $\langle a, b \rangle \in L \wedge type_L(\langle a, b \rangle) = r$. We also say $\langle a, b \rangle$ is a r-relationship. From the definition of inheritance, if $\langle a, b \rangle \in {}_r M$, $type_E(a) \in_{\sqcap_{r.source}} M \wedge type_E(b) \in_{\sqcap_{r.target}} M$
- For a reference r,

  $$ran_r(x) \equiv \{\langle x, y \rangle \in_r M\}, \quad dom_r(x) \equiv \{\langle y, x \rangle \in_r M\}$$

- For a set of references Y,

  $$ran_Y(x) \equiv \{\langle x, y \rangle | \langle x, y \rangle \in_r M \wedge r \in Y\},$$
  $$dom_Y(x) \equiv \{\langle y, x \rangle | \langle y, x \rangle \in_r M \wedge r \in Y\}$$

  If $\forall r \in Y(type_L(e) \notin \sqcap_{r.source})$, $ran_Y(e)$ is undefined; and if $\forall r \in Y(type_L(e) \notin \sqcap_{r.target})$, $dom_Y(e)$ is undefined.
- For a set G of references, if $\langle x, y \rangle \in {}_G L$, we say $x \rightsquigarrow_G y$; if $x \rightsquigarrow_G y$ and $y \rightsquigarrow_G z$, then $x \rightsquigarrow_G z$.

3.2. Generation constraints

In this paper, model generation is regarded as a process of producing a model $M = (E, L, type_E, type_L)$ according to a *metamodel* $\mathcal{M} = (T, H, A, R, C, assoc, mult, \prec)$ and a set of *options*, i.e., some *constraints*. Those constraints are used to guide the generation process.

Syntactic constraints. A generated model is said to be *correct* if it conforms to the syntactic and the semantic constraints imposed by the metamodel. A metamodel $\mathcal{M}$ imposes three kinds of syntactic constraints which can easily be extracted from the definitions presented in Section 3.1:

- *Element syntactic constraint*: the element type must be valid, i.e.,

  $$\forall e(e \in E \rightarrow type_E(e) \in T - H)$$

- *Attribute syntactic constraint*: the type of the attribute value must be valid, i.e.,

  $$\forall a, e(a : t \rightarrow d \in A \wedge e \in_{\sqcap_t} \rightarrow a(e) \in I_d)$$

- *Relationship syntactic constraint*: the relationship type and the multiplicity must be valid, i.e.,
  1. $\forall \langle a, b \rangle (\langle a, b \rangle \in L \rightarrow type_L(\langle a, b \rangle) \in R)$;
  2. for each $r \in R$, when $mult(r) = (\langle ls, us \rangle, \langle lt, ut \rangle)$

     $$\forall a(a \in_{\sqcap_{r.source}} M \rightarrow lt \leq |ran_r(a)| \leq ut),$$
     $$\forall b(b \in_{\sqcap_{r.target}} M \rightarrow ls \leq |dom_r(b)| \leq us)$$

Semantic constraints. A correct model must also conform to the semantic constraints implied by the metamodel, though they may not be defined explicitly. We identify four most common semantic constraints on any set G of references:

- *Reflexivity*: G is *non-reflexive* implies $\forall \langle e_s, e_t \rangle (\langle e_s, e_t \rangle \in {}_G M \rightarrow e_s \neq e_t)$.
- *Ordering*: G is *ordered* implies for any two elements e_1, e_2 in M the following condition always hold $e_1 \rightsquigarrow_G e_2 \rightarrow \neg e_2 \rightsquigarrow_G e_1$.
- *Necessity*: if G is *target-necessary*, when $ran_G(a)$ is defined, $\forall a(a \in E \rightarrow |ran_G(a)| > 0)$. if G is *source-necessary*, when $dom_G(b)$ is defined, $\forall b(b \in E \rightarrow |dom_G(b)| > 0)$
- *Uniqueness*: if G is *target-unique*, when $ran_G(a)$ is defined, $\forall a(a \in E \rightarrow |ran_G(a)| \leq 1)$. if G is *source-unique*, when $dom_G(b)$ is defined, $\forall (b \in E \rightarrow |dom_G(b)| \leq 1)$.

The four constraints above can also be applied to a single reference r by regarding r as a singleton list $\{r\}$.

For example, the set C of all containment references is *non-reflexive, ordered, source-necessary* (except for the root element), and *source-unique*; inheritance is *non-reflexive* and *ordered*. By default, a reference is *reflexive, not ordering, not necessary*, and *not unique*.

Range constraints. When the model is going to serve as the input of performance testing, we must control its size, including the amounts of elements and relationships, and the value domains of attributes. We term these kinds of constraints *range constraints*. Our approach supports three range constraints:

- *Element range constraint*: for any class c, $range_c$ denotes an element range constraint on c, which prescribes that $|\{e \in {}_c M\}|$ must be a value contained in $range_c$;
- *Relationship Range Constraint*: for any set G of references, $range_G$ denotes a relationship range constraint on G, which prescribes that $|\{\langle a, b \rangle | \langle a, b \rangle \in {}_G M\}|$ must be a value contained in $range_G$;
- *Value Range Constraint*: for any attribute a: $t \rightarrow d$, $range_a$ denotes a value range constraint, which limits the value domain of a, i.e., $\forall e \in_{\sqcap_t} M(e(a) \in range_a)$

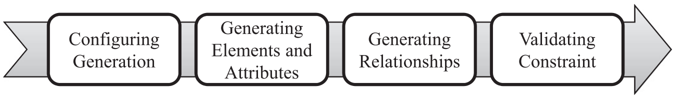


Fig. 5. Approach overview.

It is worthwhile to notice that range constraints might not always be satisfied if they conflict with others. For instance, a relationship range constraint may be defined to restrict the amount of relationships. If the required amount is smaller or larger than the model could have, our approach would determine to break this constraint at runtime to create a correct output.

4. Approach to test data generation

The overview of our approach can be depicted as Fig. 5 with four major phases below:

The first phase is to configure the generation. In this phase, users establish a configuration model, containing reference semantic constraints and user-defined constraints. User-defined constraints include both range constraints and extra constraints. The configuration model and the metamodel are used to guide model production.

The second phase is the element and attribute generation phase. Based on the syntactic and the range constraints, our approach creates model elements and sets their attributes.

In the third phase, all relationships will be generated. This phase contains three sub-phases: 1) instantiating containment references (i.e., ordered, non-reflexive, source-necessary, and source-unique references); 2) instantiating constrained references according to semantic constraints and range constraints derived from the configuration model; 3) instantiating normal references. Although there are three sub-phases, all of the three employ a unified algorithm with different parameters to handle relationship generation.

The last phase is the validation phase. All user-defined extra constraints will be checked in this phase because our approach could not solve those constraints during model generation. If the produced model satisfies those constraints, it will be returned as the final result. Otherwise, our approach will return an empty model and report errors.

4.1. Configuration

This subsection discusses how to configure the model generation process with a configuration model. Let us define the configuration model using Meta Object Facility (MOF, Object Management Group (2011)) first. Its definition is shown in Fig. 6. The class *ConfigurationModel* represents a configuration of our approach. It contains a reference to *Class* specifying the possible classes whose elements can be roots. And the property *uniqueRoot* specifies if there should be only one root element in the generated model. A *ConfigurationModel* can own four kinds of constraints, i.e., *ElementRangeConstraints, RelationshipConstraints, GlobalRangeConstraints*, and *ExtraConstraints*.

ElementRangeConstraint restricts the amount of elements owning the same type. The element type is specified by the relationship *class* from *ElementRangeConstraint* to *Class* (defined in MOF). Each *ElementRangeConstraint* may also contain some *AttributeRangeConstraints* each of which denotes a value range constraint. The attribute to be constrained is specified by the relationship *attribute*. The class *RelationshipConstriant*, which combines the semantic constraint and relationship range constraints, is used to guide generating relationships. Note that containment references cannot be imposed any constraints explicitly because they are constrained in a default manner.

A *GlobalRangeConstraint* is used to specify default range constraints, including the *total size*, the *default element range*, the *default relationship range*, and the *default value range* (for different data types, e.g., integer and string). *Total size* specifies the total number of elements in the generated model. *Default element range* specifies the number of elements for any kind. If there is no existence of an *ElementRangeConstraint* for a certain class, the default range will be used. *Default relationship range* and *default value range* are similar to that case.

ExtraConstraints represent the constraints not discussed in this paper. They must be written as OCL invariants. Our approach could not solve those constraints during model generation, which will be used to validate the generated model.

ElementRangeConstraint, AttributeRangeConstraint, ReferenceConstraint, and *GlobalRangeConstraint* are subclasses of *Bound*. Formally, a *Bound* can be defined as a set $\{(v_i, p_i)\}$, where $\sum_i p_i = 1 \wedge p_i \geq 0$. Each pair (v, p) in the *Bound* can be interpreted as *the probability of selecting the value v is p*, where p is termed *selection probability*. To select a value from a *Bound*, generate a random non-

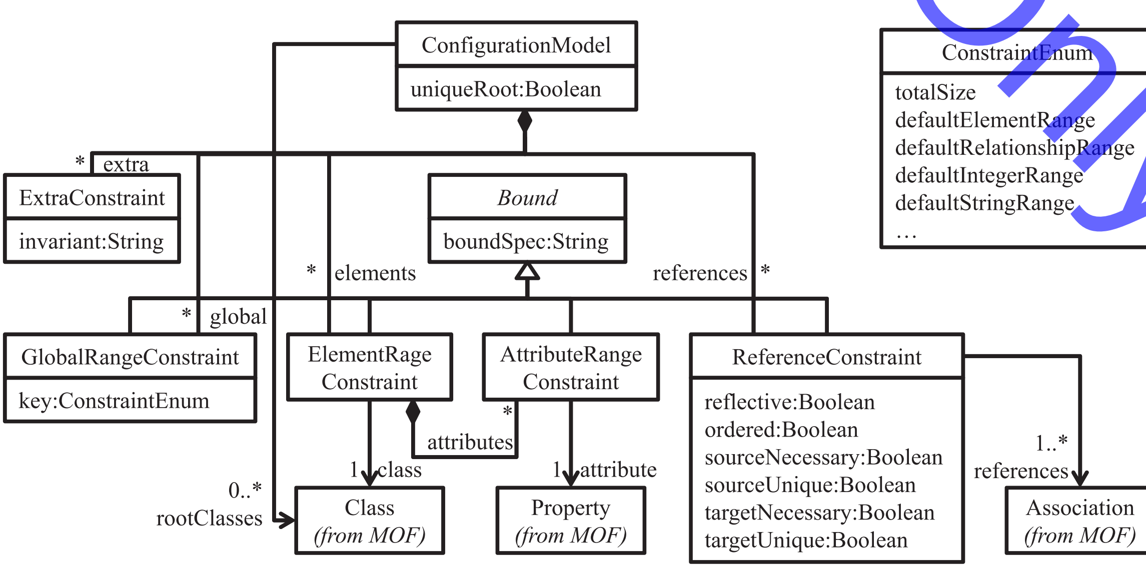


Fig. 6. Configuration model.

negative number r first, and then return the value v_i that satisfies $\Sigma_{j<i} p_j \le r < \Sigma_{j \le i} p_j$.

In the configuration model, a *Bound* is specified in the textual form. Its grammar can be defined as follows:

$$\begin{array}{rcl}
bound & ::= & bList \\
item & ::= & bItem \mid pbItem \\
pbItem & ::= & bItem : probability \\
bItem & ::= & bList \mid bRange \mid literal \\
bList & ::= & \{\ item\ (,\ item)*\ \} \\
bRange & ::= & [\ literal\ ..\ literal\ ] \\
literal & ::= & any\ constant\ for\ a\ data\ type \\
probability & ::= & a\ real\ number\ from\ 0\ to\ 1
\end{array}$$

where *bList* represents a list of possible values and *bRange* represents a value range defined by a minimum and a maximum value. All the values in the same *bRange* share the same selection possibility. *bItem* represents an item (a literal, a list, or a range) whose possibility is not defined explicitly (its possibility is deduced from other items).

The *Bound* specified in this form can be converted into the set of pairs based on which the value selection progress has been explained above. For example, `{3,5:0.2,[7..9]:0.3}` can be translated into

`{(3,0.5), (5,0.2), (7,0.1), (8,0.1), (9,0.1)}`

Please see Algorithm 11 in Appendix for more information.

4.2. Element and attribute generation

The second phase is to generate model elements and attributes. In short, for each non-abstract class t in the metamodel $\mathcal{M}$, create s_t elements. Then, for each attribute a of t and an element e, randomly assign a value to $a(e)$, where s_t denotes the number of t-elements in the produced model. The basic element generation algorithm is described in Algorithm 1.

Algorithm 1: GenerateElements(T)

```
Input: T, the set of classes
Output: E, the set of elements
foreach t ∈ T do
    s_t ← the number of elements to be generated;
    for i ← 0; i < s_i; i ← i + 1 do
        e ← a new instance of t;
        foreach a : t → t_d do
            range_a ← the value range constraint for a;
            val ← a value randomly selected from range_a;
            a(e) ← val;
        E ← E ∪ {e};
return E;
```

The algorithm is not difficult. However, the difficulty is to determine s_t for each class t. If s_t is not assigned properly, the model may not be correctly generated. It is because that the metamodel and the configuration model impose some constraints as follows:

First, let

$$S_t \equiv \sum_{o \in \sqcap_t} s_o$$

Second, for any class t whose instances could not be root elements, S_t is determined by the number of all possible containers, i.e.,

$$\sum_{r \in L_C(t)} (lt_r \times S_{r.source}) \le S_t \le \sum_{r \in U_C(t)} (ut_r \times S_{r.source})$$

where $L_C(t) = \{r | r \in C \wedge r.target \in \sqcap_t\}$, $U_C(t) = \{r | r \in C \wedge r.target \in \sqcup_t \cup \sqcap_t\}$, and for each $r \in L_C(t) \cup U_C(t)$, $(\langle ls_r, us_r\rangle, \langle lt_r, ut_r\rangle) = mult(r)$.

Third, for two classes s, t, S_s and S_t are also constrained by the multiplicity of the non-containment reference r, where $\langle s, t\rangle = assoc(r)$ and $(\langle ls, us\rangle, \langle lt, ut\rangle) = mult(r)$, i.e.:

$$ut \times S_s \ge ls \times S_t \wedge us \times S_t \ge lt \times S_s$$

Fourth, for each class t, s_t must be a value in $range_t$, where $range_t$ denotes the *bound* specified by the corresponding *ElementRangeConstraint* or the *default element range* if the *ElementRangeConstraint* is missing. Note that this requirement is flexible because our approach may break it to ensure the correctness.

At last, if *total size* is defined as a *GlobalRangeConstraint*, the sum of all s_t must meet this constraint.

To generate a valid model randomly, we must solve those range constraints (i.e., determining the value of s_t for each class t). We can employ the constraint solver to find a random solution for a set of constraints. According to the solution, we can determine s_t for each class t.

4.3. Relationship generation

The third phase is to generate the relationships of the model M, which is described in Algorithm 2. It has three sub-phases, i.e., generating containment relationships (line 2), constrained relationships (line 5), and normal relationships (line 7), based on the semantics and the constraints defined in the configuration model.

Algorithm 2: EntryOfGenerateRelationships(R, C)

```
  Input: R, the set of references; C, the set of containment
         references
1 L ← C;
2 GenerateContainmentRelationships(C);
3 foreach ReferenceConstraint cons in the configuration model do
4     L ← L ∪ cons.references;
5     GenerateConstrainedRelationships(cons);
6 foreach r ∈ R − L do
7     GenerateOtherRelationships(r);
```

First, let us consider the containment references. All containment references are non-reflexive, ordered, source-unique, and source-necessary (except for the roots), so for all containment references we can handle them as Algorithm 3 . *parents* are all possi-

Algorithm 3: GenerateContainmentRelationships(S)

```
Input: S, the containment reference set
E ← the set of elements;
RT ← the root classes specified in the configuration model;
parents ← E;
children ← E;
possibleRoots ← {e | e ∈ E ∧ ∃t(t ∈ RT ∧ type_E(e) ⪯ t)};
if the model could have only one root element then
    numberOfRoot ← 1;
else
    numberOfRoot ← an integer from 1 to |E| − 1;
randomly remove numberOfRoot elements included in
    possibleRoots from children;
size ← |E| − numberOfRoot;
GenerateRelationships(S, parents, children, true, true, false,
    false, false, true, size);
```

ble container elements; *children* are all possible children elements. They are initialized by E, the element set of M (line 1 to 4). In line 5, we collect the possible root elements. From line 6 to 9, we calculate the number of root elements (i.e., *numberOfRoots*) based on the value of *uniqueRoot* specified in the configuration model. In line 10, we select *numberOfRoots* elements from *possibleRoots* and remove them from *children* (a root does not require a parent). The actual generation logic is realized by calling *GenerateRelationships* (in line 12), according to the semantic constraints of containment references. We will discuss *GenerateRelationships* later.

Second, we generate some relationships based on the *RelationshipConstraints* defined in the configuration model. Since a *RelationshipConstraint* specifies the semantic constraints and the range constraint on a set of references, we simply extract the necessary information and use it as the actual parameters of *GenerateReferences*. This process can be described in Algorithm 4. For each *RelationshipConstraint*, we collect the possible source and target elements (line 3 and 4), and randomly select the number of relationships to be generated (line 5). Then, similar to Algorithm 3, we call *GenerateReferences* and employ the information provided by the constraint as the parameter (line 6).

Algorithm 4: GenerateConstrainedRelationships(*cons*)

Input: *cons*, a *RelationshipConstraint*
1 $E \leftarrow$ the set of elements;
2 $refs \leftarrow$ the references related to *cons*;
3 $src \leftarrow \{e | e \in E \wedge \exists r (r \in refs \wedge type_E(e) \preceq r.source)\}$;
4 $tar \leftarrow \{e | e \in E \wedge \exists r (r \in refs \wedge type_E(e) \preceq r.target)\}$;
5 $size \leftarrow$ a value selected from the range constraint of *cons*;
6 GenerateRelationships($refs$, src, tar, $cons.sourceUnique$, $cons.sourceNecessary$, $cons.targetUnique$, $cons.targetNecessary$, $cons.reflexive$, $cons.unique$, $size$);

In the last sub-phase, we handle the remainder references with default relationship constraints (i.e., reflexive and unordered). This procedure is described in Algorithm 5.

Algorithm 5: GenerateOtherRelationships(r)

Input: r, a reference
Output: the produced relationships
1 $E \leftarrow$ the set of elements;
2 $src \leftarrow \{e | e \in E \wedge type_E(e) \preceq r.source\}$;
3 $tar \leftarrow \{e | e \in E \wedge type_E(e) \preceq r.target\}$;
4 $size \leftarrow$ a value selected from the range constraint for r;
5 GenerateRelationships($\{r\}$, src, tar, false, false, false, false, true, false, $size$);

As mentioned above, the core generation logic is realized by the function *GenerateRelationships*, which has been called in Algorithm 3, 4, and 5. The basic idea of *GenerateRelationships* is as follows: 1) randomly select a reference r; 2) randomly pick a source element e_s and a target element e_t from the element set N constructed by Algorithm 1; 3) establish a r-relationship $\langle e_s, e_t \rangle$ in M. However, during this process, the following two problems must be tackled: 1) how to select e_s and e_t properly in order to satisfy all the constraints on relationships? 2) how to do if there is no valid e_s or e_t?

Before going on, we have to define two auxiliary functions *IsForbidden* and *SelectCandidate*. *IsForbidden* checks if two elements e_s and e_t can be connected with a r-relationship without violating reflexivity and ordering constraints (as described in Algorithm 6). *IsCandidate* is used to check if an element e can be the (source or target) end of a r-relationship without breaking the upper bound, as well as the necessity and the uniqueness constraints.

Algorithm 6: IsForbidden(*S*, e_s, e_t, *reflexive*, *ordered*)

Input: S, is a reference set; e_s and e_t, the candidate source and target element; $reflexive$ and *ordered*, semantic constraints on S
Output: whether the two semantic constraints will be violated after $\langle e_s, e_t \rangle$ is created
1 **if** $reflexive = false$ *and* $e_s = e_t$ **then return** true;
2 **else if** $ordered = true$ *and* $e_t \rightsquigarrow_S e_s$ **then return** true;
3 **else return** false;

IsCandidate has two versions, i.e., *IsSrcCandidate* and *IsTarCandidate*. Algorithm 7 presents *IsSrcCandidate*. It is responsible for checking if an element e can be the source end or not. If e has fulfilled the lower bound and there exists another element e' not satisfying the lower bound, e could not be a valid source (line 4, 6, and 7). It is our algorithm that gives the elements that do not satisfy the lower bound top priority to be used to create relationships. That is intended for ensuring all the elements reach their lower bounds. *IsTarCandidate*, which selects the target end, is similar to this algorithm. However, it uses $dom_{\Box}(e)$, ls_r, and us_r to replace $ran_{\Box}(e)$, lt_r, and ut_r respectively.

Algorithm 7: IsSrcCandidate(r, e, *unique*, *necessary*)

Input: r, a reference; e, the element to be checked; *necessary* and *unique*, semantic constraints focused by this algorithm
Output: whether the element that can be the source end of a new r-relationship
1 $S \leftarrow$ the reference set containing r;
2 $(\langle ls_r, us_r \rangle, \langle lt_r, ut_r \rangle) \leftarrow mult(r)$;
3 $U \leftarrow$ {candidate elements, each of which does not violate the upper bound and the semantic constraints, and has not been marked as an invalid candidate};
4 $C_L \leftarrow \{o | o \in U \wedge ((unique \rightarrow |ran_S(o)| = 0) \wedge (|ran_r(o)| < lt_r) \vee (necessary \wedge |ran_G(o)| = 0)))\}$;
/* the candidate elements do not satisfy their lower bounds */
5 $C_U \leftarrow \{o | o \in U \wedge \neg unique \wedge lt_r \leq |ran_r(o)| < ut_r \wedge \neg(necessary \wedge |ran_S(o)| = 0)\}$;
/* the candidate elements satisfy the lower bounds but not satisfy their upper bounds */
6 **if** $C_L \neq \emptyset$ **then return** whether C_L contains e;
7 **else if** $C_U \neq \emptyset$ **then return** whether C_U contains e;
8 **else return** false;

Now, let us consider the details of *GenerateRelationships*. It can be described briefly as Algorithm 8 . It will not stop producing relationships until the termination condition is satisfied. When producing a new relationship, it firstly tries to find two elements that can compose a valid r-relationship (line 5 and 6). During this process, it employs Algorithms 6 and 7 to select proper elements. For example, as shown in Fig. 7(a), it is a simple metamodel containing two classes A and B, and a containment reference r from A to B. The metamodel prescribes that each A element must be associated with at least one B element. As shown in Fig. 7(b), it is an intermediate result including two A and two B elements. A r-relationship $\langle e_1, e_3 \rangle$ has been produced, and now we try to generate the second one. According to our algorithm (line 5), only e_2 and e_4 are the valid candidates. Otherwise, if we chose e_1 and e_4, and established a relationship, we would not get a valid result because no other

Algorithm 8: GenerateRelationships(*S, src, tar, srcUnique, srcNecessary, tarUnique, tarNecessary, reflexive, ordered, size*)

Input: *S*, a reference set; *src*, the set of source elements; *tar*, the set of target elements; *size*, the number of relationships to be generated; *srcUnique*, *srcNecessary*, *tarUnique*, *tarNecessary*, *reflexive*, and *ordered*, the semantic constraints on *S*

1 $L \leftarrow$ the set of relationships of model M;
2 **repeat**
3   **if** $S = \emptyset$ **then return** L;
4   $r \leftarrow$ a reference selected from S randomly, which satisfies $\forall e(lt_r \leq |ran_r(e)| \wedge ls_r \leq |dom_r(e)|) \rightarrow \nexists r' \exists e(|ran_{r'}(e)| < lt_{r'} \vee |dom_{r'}(e)| < ls_{r'})$;
5   $e_s, e_t \leftarrow$ two elements selected from src and tar, where $IsSrcCandidate(r, e_s, tarUnique, tarNecessary) \wedge IsTarCandidate(r, e_t, srcUnique, srcNecessary) \wedge \neg IsForbodden(S, e_s, e_t, reflexive, ordered)$;
6   **if** *such* e_s *and* e_t *can be found* **then** $L \leftarrow L \cup \{\langle e_s, e_t \rangle\}$;
7   **else if** *only* e_s *exists* **then**
8   fix the model with $\langle e_s, r \rangle$
9   **else if** *only* e_t *exists* **then**
10   fix the model with $\langle r, e_t \rangle$
11   **else** $S \leftarrow S - \{r\}$;
12 **until** *all the elements in src and tar have satisfied their lower bounds and (all the elements have reached to their upper bounds or size relationships have been produced)*;

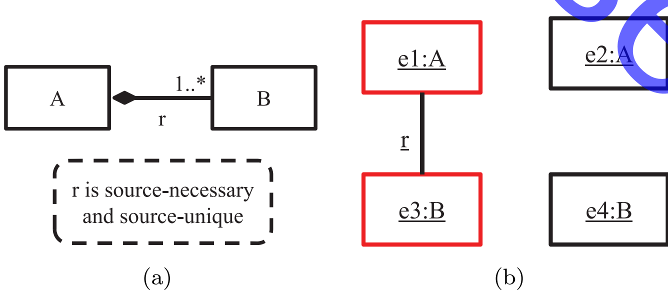


Fig. 7. An example of element selection.

B element can be associated with e_2. Such an element selection strategy is intended for fulfilling the lower bound requirement.

If the condition in line 5 is partially satisfied, i.e., there does not exist any e_s or e_t satisfying the condition (line 7 and 9), we tries to *fix* the model by removing an existing relationship so that two new relationships can be appended without breaking bound and semantic constraints. The fixing procedure, which is intended for adjusting the model to append a new relationship, will be discussed in detail in the next subsection. If the *fixing* job fails, mark e_s or e_t as an invalid candidate of r.

If the condition in line 5 is totally unsatisfied, remove r from S so that it would not be chose again.

The algorithm will terminate when: 1) G is empty; 2) all elements have reached to their upper bounds (i.e. no more relationship can be produced) or *size* relationships have been produced. And this algorithm *does* terminate, because during each iteration a new relationship will be produced, an element is removed from the candidate set, or a reference is removed. This means the termination conditions will eventually be satisfied.

4.4. Model fixing

As shown in Algorithm 8, it is possible that only e_s or e_t (but not both at the same time) is found. Note that such a phenomenon

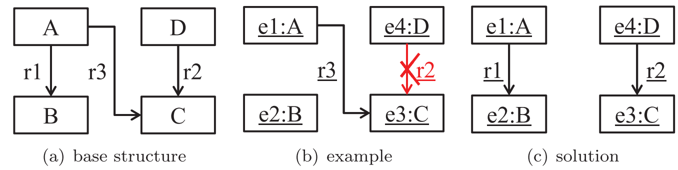


Fig. 8. The first exceptional base structure and an example.

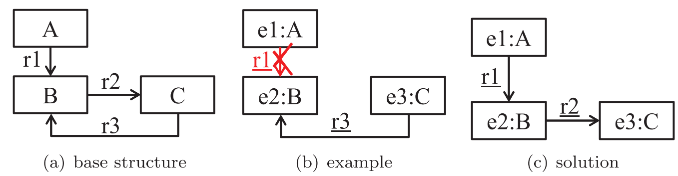


Fig. 9. The second exceptional base structure and an example.

does not always create a problem. However, if it is caused by an improperly created relationship and hinders the subsequent generation job, it must be *fixed* (line 8 and 10 in Algorithm 8). There are two base structures that, though not necessarily, might result in this problem.

Before going on, we define a new concept named *co-evolved references*.

Definition 3. Co-evolution A set G of references is source co-evolved, if and only if there exists a constant c_1 let $\forall e(|dom_G(e)| < c_1)$ hold; G is target co-evolved, if and only if there exists a constant c_2 let $\forall e(|ran_G(e)| < c_2)$ hold.

Obviously, source-uniqueness and target-uniqueness are special cases of *co-evolution*.

The first base structure. Fig. 8 (a) presents the first exceptional base structure: there are four classes (A, B, C, and D) and three references (r1, r2, and r3). When r2 and r3 are source co-evolved, and r1 and r3 are target co-evolved, a problem may take place when creating a r2-relationship for a D element or when creating a r1-relationship for a B element.

For example, as shown in Fig. 8(b), a problem arose when creating a r2-relationship starting from e4, provided that r1, r2, and r3 are source-unique, and $\forall e(|ran_{\{r1,\ r3\}}(e)| \leq 1)$. In this case, e3 is required by the attempt to creating a r2-relationship from e4, however it has already been connected to e2 by a r3-relationship. Since e3 can only be connected to either e2 or e3 (source uniqueness), a conflict occurs.

It is obvious that the r3-relationship is the cause of this problem. To handle this conflict, a possible solution for this example, as shown in Fig. 8(c), is as follows: 1) remove this r3-relationship to release e3; then 2) create a r2-relationship $\langle e4,\ e3 \rangle$ and a r1-relationship $\langle e1,\ e2 \rangle$. The reason why we must create a r1-relationship is to ensure that the fixing procedure always increases the number of relationships. Such a fixing procedure is listed in Algorithm 9.

As mentioned above, for the structure in Fig. 8(a), a problem may also happen when creating a r1-relationship for a B element. It is because that all the A elements may have been consumed by r3-relationships (r1 and r3 are target co-evolved). The solution to this case is similar to the former as shown in Algorithm 12 in Appendix. Actually, it can be regarded as a *dual* of Algorithm 9 by reverting the direction of all the references in Fig. 8(a).

The second base structure. The second exceptional base structure is related to *ordering*. As shown in Fig. 9(a), there are three class (A, B, and C) and three references (r1, r2, and r3). If r1, r2, and r3 are ordered, source unique, and source necessary (actually, they

Algorithm 9: FixingModelForCase1(e_s, r)

Input: e_s, a candidate source element; r, a reference to be initialized

$E \leftarrow$ the set of elements in the model;
$L \leftarrow$ the set of relationship in the model;
$S \leftarrow$ the set of references being focused on;
$cons \leftarrow$ the relationship constraint on S;
foreach $\langle e_x, e_y\rangle \in_S$ *the model* **do**
  if $\neg IsForbidden(S, e_s, e_y, cons.reflexive, cons.ordered)$, *and* $IsTarCandidate(r, e_y, cons.srcUnique, cons.srcNecessary)$, *provided that* $\langle e_x, e_y\rangle$ *is removed* **then**
    foreach $e_z \in E$ *and* $r' \in S$ **do**
      if $\neg IsForbidden(S, e_s, e_z, cons.reflexive, cons.ordered)$ *and* $IsSrcCandidate(r', e_x, cons.tarUnique, cons.tarNecessary)$ *and* $IsTarCandidate(r', e_z, cons.srcUnique, cons.srcNecessary)$, *provided that* $\langle e_x, e_y\rangle$ *was removed* **then**
        if *the type constraints are satisfied* **then**
          $L \leftarrow L - \langle e_x, e_y\rangle + \{\langle e_s, e_y\rangle, \langle e_x, e_z\rangle\}$, where $\langle e_s, e_y\rangle$ is a r-relationship and $\langle e_x, e_z\rangle$ a r'-relationship;
          return;
mark e_s as an invalid source of r;

Algorithm 10: FixingModelForCase2(e_s, r)

Input: e_s, a candidate source element; r, a reference to be initialized

$E \leftarrow$ the set of elements in the model;
$L \leftarrow$ the set of relationship in the model;
$S \leftarrow$ the set of references being focused on;
$cons \leftarrow$ the relationship constraint on S;
foreach $e_u \in E$ **do**
  if *there exist* $e_x, e_y, e_z \in E$ *and* $r' \in S$ *that* $e_u \rightsquigarrow_S e_x$, $\langle e_x, e_y\rangle \in_S L$, *and* $e_y \rightsquigarrow_S e_z$ *hold* **then**
    if $IsSrcCandidate(r', e_z, cons.tarUnique, cons.tar.Necessary)$ *and* $IsTarCandidate(r, e_y, cons.srcUnique, cons.srcNecessary)$ *and* $IsTarCandidate(r', e_u, cons.srcUnique, cons.srcNecessary)$ *and* $\neg IsForbidden(S, e_s, e_y, cons.reflexive, cons.ordered)$, *provided that* $\langle e_x, e_y\rangle$ *was removed* **then**
      if *the type constraints are satisfied* **then**
        return;
mark e_s as an invalid source of r;

are containment references), a problem may occur when creating a r1-relationship for an A element or creating a r2-relationship for a C element.

Fig. 9(b) shows an example. If we want to create a r1-relationship from e1 to e2, there would be a conflict because e2 has been consumed by a r3-relationship from e3. This problem can also be interpreted from another point of view: assuming that we are going to create a r2-relationship for e3, there is a conflict because all B elements have become the succeeding nodes of e3.

However, the problem is interpreted, the possible solution, as shown in Fig. 9(c), remains the same. In the figure, $\langle e_3, e_2\rangle$ is removed, and $\langle e_1, e_2\rangle$ and $\langle e_2, e_3\rangle$ are created. The fixing procedure is listed in Algorithm 10. As for the case of creating a r2-relationship for e3, the fixing procedure, as shown in Algorithm 13 in Appendix, is similar to the logic mentioned above.

Structure conversion. The structures presented above are two basic cases, while a metamodel may contain more complex fragments that cannot be enumerated thoroughly. Fortunately, it is possible to convert complex cases into the two basic cases by applying a set of *conversion* operators. The problem that occurs in the original fragment will also happen after appropriate conversion, and the solutions that are designed for the basic cases are also applicable to the complex cases. The rest of this section proposes some *conversion* operators and demonstrates how to solve conflicts by converting a metamodel into basic cases using those operators.

Operator 1 (Inheritance removal)**.** Assume that there are two classes c_1 and c_2, where $c_1 \prec c_2$. After applying this operator: 1) the inheritance between c_1 and c_2 is removed; 2) $\forall r_i = \langle c, c_2\rangle$ is *split* into $r_i = \langle c, c_2\rangle$ and $r'_i = \langle c, c_1\rangle$; 3) $\forall r_o = \langle c_2, c\rangle$ is *split* into $r_o = \langle c_2, o\rangle$ and $r'_o = \langle c_1, o\rangle$. This operator is used to eliminate inheritances.

When a reference r is *split* into r and r', its semantic constraints are preserved. Besides, two constraints, i.e., $\forall e(|ran_{\{r,r'\}}(e)| \le ut_r)$ and $\forall e(|dom_{\{r,r'\}}(e)| \le us_r)$, are appended, provided that $mult(r) = (\langle ls_r, us_r\rangle, \langle lt_r, ut_r\rangle)$. If there has already been a constraint $|ran_{\{r,\ldots\}}| \le c$ (or $|dom_{\{r,\ldots\}}| \le c$), the constraint would turn into $|ran_{\{r,r',\ldots\}}| \le c$ (or $|dom_{\{r,r',\ldots\}}| \le c$).

Operator 2 (Reference folding)**.** Assume that there two classes c_1, c_2, and c_3, and two references $\langle c_1, c_2\rangle$ and $\langle c_2, c_3\rangle$. After applying this operator: 1) $\langle c_1, c_2\rangle$ is hidden; 2) c_1 and c_2 are merged, including the references related to c_1 and c_2. This operator is used to hide the unnecessary part that will not help to solve the conflict.

Operator 3 (Class division)**.** Assume that there is a class c and a reference $\langle c, c'\rangle$ (or $\langle c', c\rangle$). After applying this operator: 1) c is split into c and c''; 2) $\langle c, c'\rangle$ (or $\langle c', c\rangle$) turns into $\langle c'', c'\rangle$ (or $\langle c', c''\rangle$).

Note that the operators mentioned above are not intended to *modify* the metamodel but to make the solutions of the basic cases fit it. Fig. 10 shows some examples:

- For Fig. 10(a), a conflict may occur when a r2-relationship is being created. After applying *inheritance removal* (Fig. 10(b))) and *class division* (Fig. 10(c)), we can convert Fig. 10(a) into a structure that is isomorphic to the first basic case so that we can use the the corresponding solution to handle it.
- For Fig. 10(d), we may encounter a problem when creating a r1-relationship targeting at a C element. Similar to the former example, after applying *inheritance removal* (Fig. 10(e)) and *class division* (Fig. 10(f)), we can use the solution of the first basic case to deal with it (note that during this process $r2'$ should be ignored).
- The third example as shown in Fig. 10(g) shares some common ideas with the former two, while it is more complicated. It can also be converted into the first basic structure with *inheritance removal* (Fig. 10(h)) and *class division* (Fig. 10(i)) to solve the problem which we attempt to create a $r1$-relationship targeting at a D element.
- The last one, as shown in Fig. 10(j) and Fig. 10(k), demonstrates how to fold containment references. With the help of *reference folding*, we can fold a cycle of containment references into the second basic structure.

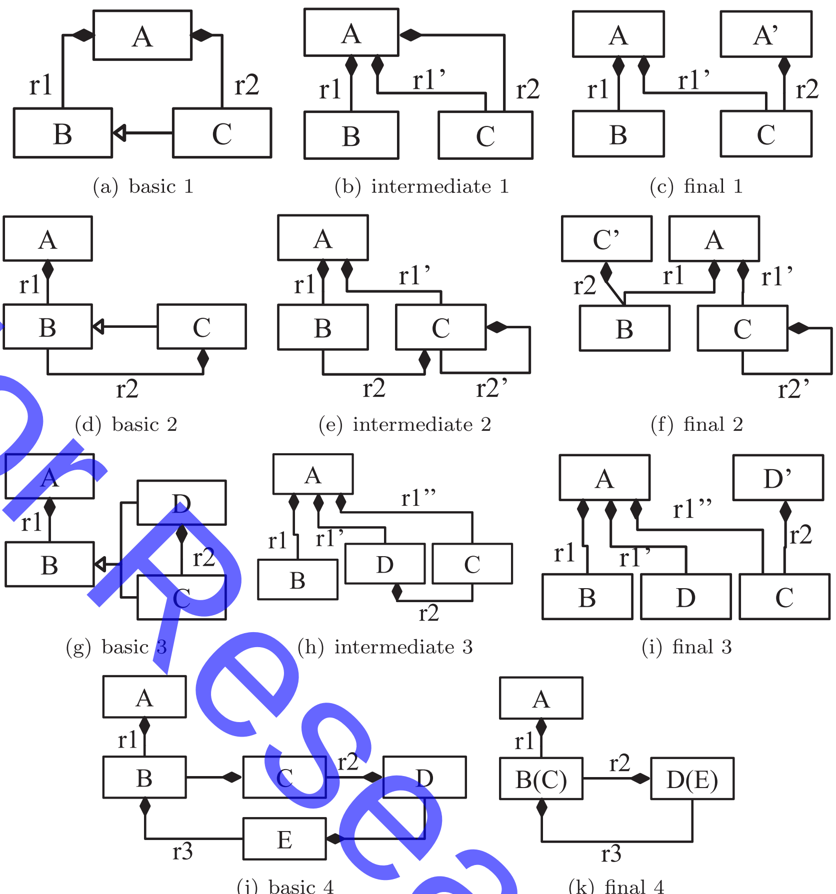


Fig. 10. Examples of model conversion.

4.5. Constraint validation

The final step of our approach is to validate if the model generated fulfils all the constraints, including syntactic constraints, semantic constraints, and user-defined constraints. Violating any constraint, the model will be rejected, and an error message will be reported to users. User-defined constraints (especially complex OCL constraints) are most likely to be violated. However, since our approach mainly contributes to performance testing, such complex OCL constraints are not frequently required. Besides, if there is a conflict among relationship range constraints, our approach may also break them in order to generate a *syntactically correct* model. In most cases, our approach is able to produce a valid model.

5. Evaluation

This section presents two case studies, one experiment in randomness, two experiments in the time costs of our algorithm. The two performance experiments in Sections 5.3 and 5.4 were carried out on a computer with Intel i7 4770 CPU, 16GB RAM, and Windows 7.

5.1. Case studies

In this subsection, we present two case studies to demonstrate the feasibility and effectiveness of our test framework[5]. In the first case study, we used our framework to test the performance of an ATL transformation, while in the second we evaluated the performance of EMF Compare.

Table 1
Metrics for the ATL transformations.

Metrics	JavaSource2Table	JavaSource2Table(M)
# Transformation Rules	4	4
# Helpers	2	0
# Attribute Helpers	1	0
# Operation Helpers	1	0
# Calls to allInstances()	1	3
# Operations on Collections per Helper	1	0
# Operations on Collections per Rule	1.25	2.25

Performance of ATL Transformation. Van Amstel et al. (2011) described a method for testing performance of model transformations. This case study adopted their methodology to test an ATL transformation with the support of our performance testing framework and our model generation algorithm. The transformation to be tested is an ATL transformation named *JavaSource2Table*[6], an open-source transformation from ATL Zoo. We also created a modified transformation (*JavaSource2Table(M)*) from the original one by replacing all the *helpers* with inline expressions as a contrast in this study. Table 1 shows the metric values of the two transformations.

[5] The prototype implementation, based on Eclipse, can be found at https://bitbucket.org/ustbmde/model-generation.git.

[6] http://www.eclipse.org/atl/atlTransformations/#Java2Table (Sep. 20, 2015).

Table 2
Performance testing results of JavaSource2Table and JavaSource2Table(M).

Test Suite	JavaSource2Table	JavaSource2Table(M)
Suite 1 (200)	0.057	0.175
Suite 2 (400)	0.213	1.204
Suite 3 (600)	0.458	3.962
Suite 4 (800)	1.144	9.244
Suite 5 (1000)	1.979	17.791
Suite 6 (1200)	3.526	31.640
Suite 7 (1400)	5.689	53.248
Suite 8 (1600)	9.032	81.093
Suite 9 (1800)	13.768	115.644
Suite 10 (2000)	19.467	158.799

Table 3
Performance testing results of EMF Compare.

	JavaSource	BibTex	Extlibrary
Suite 1 (500)	1.138	2.381	3.224
Suite 2 (1000)	4.371	8.694	12.664
Suite 3 (1500)	9.953	22.350	28.822
Suite 4 (2000)	18.321	37.201	49.482
Suite 5 (2500)	29.309	57.520	76.049

Table 4
Result of randomness experiment.

	#1	#2	#3	#4	#5
JavaSource	0.85%	0.81%	0.73%	0.86%	0.74%
PetriNet	1.32%	0.97%	0.62%	0.72%	0.51%
extlibrary	0.0014%	0.0024%	0.0059%	0.0037%	0.0050%

To test the performance of the two transformations, a *TestProject* was created in our testing framework, and a launch configuration for the ATL transformation was established in Eclipse. Then, the *TestProject* was associated with the launch configuration via a *LCBasedSpecification*. After that, we created a *RandomDataGenerator* and a *ConfigurationModel* for test data generation.

A *TestSuite* element and 5 test cases were created in the testing framework. We appended the 5 test cases into the *TestSuite*. For each test case, our framework invoked the test data generator implementing the algorithm proposed in Section 4 according to the *ConfigurationModel* specified before to generate an input model. The first 5 models had 200 elements each. Then, we established the second *TestSuite* and another 5 test cases for it. In the meantime, the *ConfigurationModel* was modified to produce 5 new models containing 400 elements each. This procedure was repeated until we created 10 *TestSuites* in total.

We executed all the 10 *TestSuites* for the original transformation. For each *TestSuite*, we collected all the execution times of the five test cases and calculated the average time cost. Then, we changed the executable in the launch configuration to the modified transformation, and ran all the ten *TestSuites* again.

The result is presented in Table 2. The integers in brackets in the first column indicate the numbers of elements in the input model. For the original transformation, it spent 0.057 seconds in average in producing an output in suite 1, and 19.467 seconds in average in suite 10. For the modified transformation, it spent 0.175 seconds in average to produce an output in suite 1, and 158.799 seconds in average in suite 10.

It is evident that the modified transformation ran much slower than the original one when the model size increased. The only difference between the two transformations is that the modified transformation uses inline expressions instead of ATL *helpers* (Table 1). Since ATL will cache the results of *helpers*, the original transformation is more efficient. This result is also consistent with the results in Van Amstel et al. (2011).

We spent half a day finishing this example, including establishing the configuration models, generating test inputs, executing the transformation, and calculating the results. According to our experience, it would probably take us a couple of days to construct valid test inputs, if we do not use our approach and tool. This study also shows that our framework can support the performance testing method proposed by other researchers. Our framework facilitates performance testing of model transformations.

Performance of EMF Compare. Now assume that we want to evaluate the performance of EMF Compare, the state-of-art model comparison tool. EMF Compare is able to compare the differences between two models conforming to the same metamodel.

We used three different metamodels, JavaSource, BibTex, and extlibrary to test the comparison efficiency. Both JavaSource and BibTex were extracted from ATL Zoo, while extlibrary was extracted from a standard example of EMF.

For each metamodel, we constructed a *TestProject*. For each *TestProject*, we created five *TestSuites*, each of which included 20 *TestCases*. For each *TestCase*, we generated 2 models to be compared by EMF Compare.

We collected the time costs of executing those *TestCases* and calculated the average time costs for each *TestSuite* (in seconds). The results are shown in Table 3. The integers in brackets in the leftmost column indicate the numbers of elements the input models of the same suite have. From the table, we can conclude that the time complexity of EMF Compare is approximately $O(N^2)$, where N is the number of elements.

This case demonstrated that not only model transformations but also other model-related operations, such as model comparison, can be handled by our framework.

5.2. Experiment in randomness

Our model generation algorithm is a randomized approach. This means all the produced models are randomly constructed. The property of randomness is meaningful for estimating the average performance of a model-related operation. Hence, we conducted an experiment to evaluate the randomness of our approach. And we want to know *if it is possible to make the similarity of any pair of produced models smaller than 5%*.

We selected three metamodels, i.e., JavaSource, BibTex, and extlibrary, which were already used previously. For each metamodel, five sets of models were generated. For each set, 20 models were generated. All the models belonging to the same model set were generated according to the identical configuration. However, models in different sets have different sizes. Then, for each pair of models in the same set, EMF Compare was used to find matches. The similarity of two models is defined by

$$\#match/\#total$$

where *#match* is the number of the matches returned by EMF Compare and *#total* is the total number of elements in the model. At last, we computed the average similarity for each set, and result is listed in Table 4.

From the table, we can learn that it is possible to control the similarity of two generated models under 5% in our approach. According to our experience, to achieve this goal, the size of every possible attribute-value range had better be ten times larger than the element amount.

Table 5
JavaSource model generation performance of Alloy, EMFtoCSP, and ours.

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Ours	0.06	0.12	0.14	0.18	0.18	0.9	0.20	0.23	0.24	0.26
Alloy	0.12	0.77	2.33	5.23	9.68	17.38	29.60	45.04	61.60	73.33
EMFC	72.79	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 6
PetriNet model generation performance of Alloy and ours.

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Ours	0.06	0.11	0.21	0.32	0.47	0.65	0.88	1.15	1.41	1.76
Alloy	222.87	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

5.3. Experiment in performance: Comparative studies

In this experiment, we try to answer the question *how faster can our approach generate a model than the solver-based approaches?* Note that we did not compare our approach with other algorithm-based approaches. Their limitations have been discussed sufficiently in Wu et al. (2012). And we will discuss them in Section 7.

First, a test was conducted to compare the efficiencies of EMFto-CSP Pérez et al. (2012) and Alloy Jackson et al. (2000) with our approach's. EMFtoCSP and Alloy, the state of the art model constraint satisfiability solvers, are also used to generate test inputs for model transformations Sen et al. (2008)González et al., 2012). All the three approaches are forced to generate models conforming to the JavaSource metamodel (Fig. 12 in Appendix). And, there is no extra constraint. Note that for Alloy we equivalently translated the metamodel to the Alloy specification before the experiment.

Then, every approach generated 10 models. And, each model was repeatedly generated 5 times to obtain the average time cost. Each model has a particular amount of elements: the *i*th model has $5 \times i$ *ClassDeclarations*, $20 \times i$ *MethodDefinitions*, $125 \times i$ *MethodInvocations*, and *one JavaSource* (the root element), i.e., $150 \times i$ elements except for the root.

The result is listed in Table 5. Each cell indicates the average time cost (in seconds) for an approach (row) to generate a model (column). During this experiment, the time costs of our approach ranged from 0.06s to 0.23s; the time costs of Alloy ranged from 0.12s to 45.04s. With regard to EMFtoCSP, it failed to produce any models (except for the first one) within a reasonable time (30 minutes).

A further test was carried out to compare the efficiencies of Alloy and our approach by using the PetriNet metamodel (since our approach is apparently better than EMFtoCSP in performance). Similar to the former experiment, the two approaches were asked to generate 10 models, whose sizes increased linearly. Each model was generated 10 times by each approach to obtain the average time costs (in seconds). The result is presented in Table 6. From the table, the time cost of our approach ranged from 0.06s to 1.76s; Alloy spent 222.87s producing the first PetriNet model (containing 600 elements) but failed to produce any larger one.

According to this experiment, it is evidently that our model generation approach is *significantly more efficient* than the other two. And, we believe that our approach also has performance advantage compared to other solver-based approaches.

However, we do not claim that our model generation algorithm can take the place of the constraint solver, e.g., Alloy. The qualitative analytic result is listed in Table 7.

Alloy supports first-order-logic-based constraints, while our approach can only handle some predefined model constraints defined in Section 3.2. These predefined constraints can be encoded in Alloy codes. It means they are a subset of Alloy constraints.

Table 7
Qualitative comparison between Alloy and our approach.

	Alloy	Our approach
Constraint	First-order-logic-based	Predefined
Efficiency	Very low	Fast
Suitable testing method	White-box	Black-box
Suitable testing goal	Correctness	Performance
Correctness of produced model	Yes	Yes
Randomness of produced model	Difficult and inefficient	Yes

Alloy is more expressive and can handle more kinds of constraints. It is suitable to white-box testing which verifies the correctness of an MRO. However, it cannot produce a large model efficiently. It is infeasible to produce a model containing thousands of elements, which is used to test the performance of an MRO, with Alloy. As illustrated by this experiment, our algorithm produces a model significantly faster than Alloy does. Our algorithm is more suitable to performance testing of MROs.

If we do not consider other constraints, both Alloy and our approach can produce correct models. Besides, our approach can also produce random models (as tested in Section 5.2). Whereas, in Alloy, it is difficult and inefficient to obtain random models due to its searching strategy.

5.4. Experiment in performance: Algorithm complexity

In this experiment, we try to answer the question *what law does the performance of our algorithm follow?*

We employed our approach to generate a set of models according to 6 metamodels (without extra constraints). For each metamodel, our approach was required to produce 5 models, whose sizes ranged from 1 MB to 5 MB (approximately). And, every model was produced 5 times to obtain an average time cost (in seconds).

The six metamodels are *JavaSource, extlibrary, BibTex, PetriNet, TextualPathExp*, and *MySQL*. The first three has been used previous; *PetriNet, TextualPathExp*, and *MySQL* were also extracted from the transformations in ATL Zoo. To control the size of the model, the element and relationship range constraints of each model are fixed integers. And, all the unnecessary spaces in the output XMI files were eliminated[7].

The result of this experiment is shown in Table 8. Apparently, for different metamodels, the time costs vary a lot. The performance curves for the six metamodels are depicted as in Fig. 11. For *JavaSource*, the performance curve follows $y = 8.2474x^{2.1843}$; for *PetriNet*, the curve follows $y = 11.116x^{1.9961}$; for *extlibrary*, their curve follows $y = 2.7509x^{2.0595}$; for *BibTex*, the curve follows $y = 13.415x^{2.1608}$; for *TextualPathExp*, the curve follows $y = 41.332x^{2.36}$; for *MySQL*, the curve follows $y = 6.0276x^{2.132}$.

[7] In our previous work, we did not remove the spaces. Hence, we redid the experiment for the first three, i.e., the results are different from the old ones.

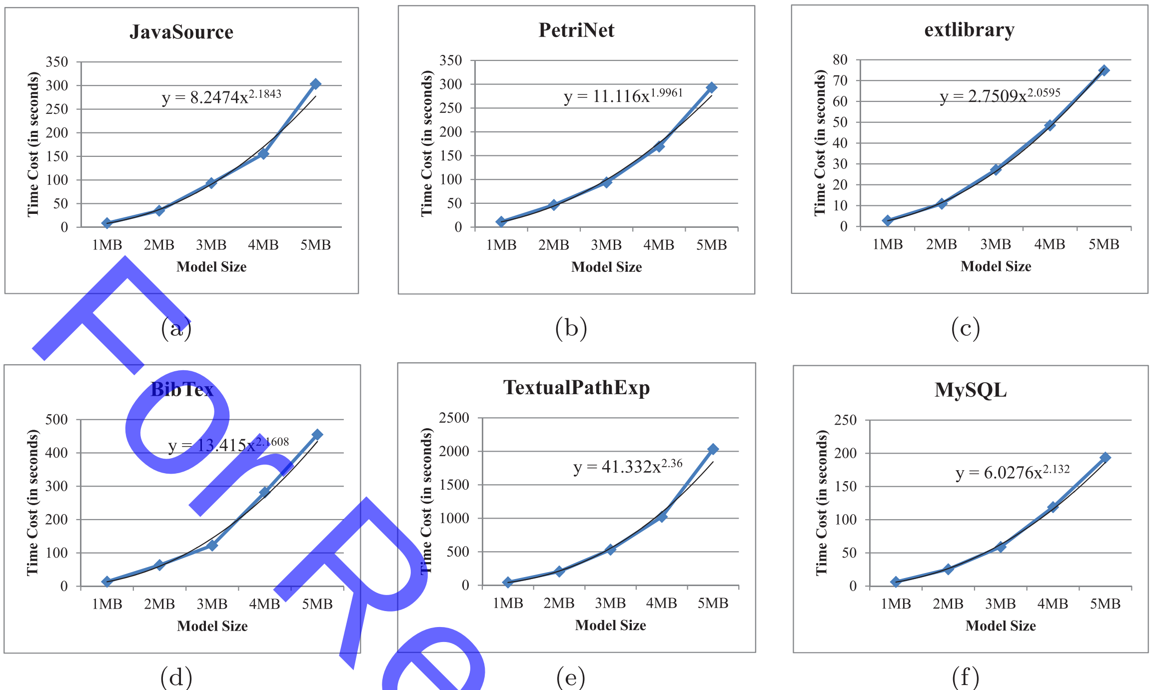


Fig. 11. Performance curves.

Table 8
Result of performance experiment 2.

	JavaS.	PetriN.	Extlib.	BibTex	TextualPE	MySQL
1 MB	8.6	11.1	2.8	13.6	43.1	6.27
2 MB	35.1	46.5	10.9	63.4	204.6	25.35
3 MB	93.3	93.7	27.2	122.3	531.5	58.97
4 MB	155.4	169.2	48.5	281.6	1021.9	118.9
5 MB	303.4	293.1	74.9	454.9	2032.7	193.41

JavaS = JavaSource; PetriN = PetriNet; Extlib = Extlibrary; TextualPE = TextualPathExp

From the result, we can learn the following things:

1. When the model size increased linearly, the times cost followed a power law $y = k \times x^p$.
2. The exponent p ranged from 1.9961 to 2.36, and its average value amounted to 2.14878 approximately. The exponent did not vary significantly.
3. For different metamodels, the coefficient k changed drastically. This implies that it is influenced by the complexity of the metamodel.

6. Discussion

Algorithm correctness. Our model generation algorithm can produce a model conforming to the syntactic constraints, semantic constraints, and user-defined range constraints, when there is *no conflict*. It will be complicated to prove this rigorously. We just discuss this qualitatively. First, our approach generates elements, attributes, and relationships based on the metamodel. Hence, the model produced satisfies the syntactic constraints (multiplicity constraints are considered below). Second, when producing relationships, our approach also takes semantic constraints into account. In line 5 of Algorithm 8, the elements selected to create a new relationship must satisfy the four semantic constraints. And it is not difficult to prove that the fixing procedures in Algorithms 9, 12, 10, and 13 will not violate the any semantic constraints, since we always check them before creating any changes. If the range constraints do not contain any conflict, Algorithms 1 and 8 will not stop until all of them are fulfilled.

Threats to validity. There are two major threats to the validity of our approach. For one thing, some advanced features in the metamodel may be an obstacle to applying our model generation algorithm. As defined in Section 3.1, only basic features, such as classes, attributes, and unidirectional references, in a metamodel are able to be handled in this paper. Advanced features, including derived attributes, *union* and *subset* of references, multidirectional references, and package import, are not supported. When a metamodel includes one of such advanced features, it cannot be instantiated by our algorithm. Although some complex metamodels, such as UML metamodel, may have those features, in most cases, we can bypass those features by replacing them with basic features, according to our experiences. For another thing, some model-related operations may have special preconditions, which may be too complex to be written in OCL, on input models. For example, a model transformation can only handle structural workflow models, while the constraint that *the model must be structural* cannot be easily achieved by a random model generator. This means that our framework based on random model generation cannot deal with the operations having such special input preconditions. It will be our future work to investigate this problem in detail.

7. Related work

7.1. Model transformation testing

Baudry et al. (2010), discussed the barriers to testing model transformation, and test data generation is one of the challenges. This paper attempts to fill this gap by proposing a testing framework of model transformations and a random model generation algorithm.

Küster et al. (2009), proposed incremental development of model transformation chains based on automated testing. They defined four test design techniques and a test framework for transformation chain. Their test framework, based on JUnit, supporting model comparison and invariant validation, is comparable to our framework. Both of the frameworks support automated testing of model transformations. However, instead of functional testing, our framework mainly focuses on performance testing. It also integrates with an automated test data generation algorithm, which is not addressed in their work.

Giner and Pelechano (2009), proposed a template of test case specifications to capture requirements for transformations, and to guide the development and documentation of model transformations. The test model proposed in this paper shares some commonalities with Giner's template, in spite of that they employ different concrete syntax to specify a test case. Our test model can also serve as a test case management mechanism, which enables us to arrange test cases into test suites.

Shelburg et al. (2013), presented an approach to regression testing for model transformations. They argued that a transformation that is changed owning to the evolution of the metamodel requires regression testing. To do so, they proposed a multi-objective optimization algorithm to generate test inputs that maximizes the coverage of the new metamodel by refactoring the existing one. We believe that our approach can cooperate with their approach. Our approach can be used to create and manage new test cases, while their approach can refactor the test cases to meet the requirements of regression testing.

Guerra proposed a specification-driven test generation approach Guerra and Soeken (2013). In this approach, one must specify the transformation properties (invariants, pre- and post-conditions) using a declarative specification language named PaMoMo. Then, those properties are solved by a proper constraint solver to derive the test input and the oracle function. Finot et al., discussed the oracle problem in transformation testing and developed a technology called partial test oracle that employs a set of model fragments (partial oracle) to determine the correctness of the test output Finot et al. (2013). Those efforts, which promoted transformation testing, targeted at white-box and functional testing. However, the test framework and the test generation algorithm proposed in this paper concentrated on performance testing of model transformations.

Van Amstel and Van Den Brand (2011), proposed three complementary techniques for the analysis of model transformations, including metrics collections, structure and dependency analysis, and metamodel coverage visualization. Their paper mainly focuses on *static analysis* of model transformations in order to improve maintainability. Our work discusses *performance testing* of model-related operations, including but not limited to model transformations.

Van Amstel et al. (2011) also reported some experimental results about the performance of QVT and ATL transformations. They compared the performance with different languages and engines, different implementation styles, and different inputs. Their paper described the methodology of performance testing in MDE. Their results can be used as a guide to improving the performance of transformations. Our work differs from theirs. This paper concentrates on the performance testing framework and the test input generation algorithm, which are ignored in their paper. However, we believe that the two papers complement one another. The framework and the model generation algorithm proposed in this paper can support the testing method described in their paper, as we have demonstrated in Section 5.1.

7.2. Model generation

Model generation (or metamodel instance generation) broadly with two technical paradigms: solver-based and algorithm-based.

Solver-based paradigm. The basic idea of solver-based approaches is as follows: 1) translate the metamodel and constraints into a formal specification that can be accepted by a model checker, a constraint solver, or a SAT/SMT solver; 2) employ those solvers to solve the specification and obtain a valid instance; 3) translate the instance found by solvers back to a model.

Alloy Jackson et al. (2000) is a mature model checker for relational logic. Since a model can be regarded as a set of elements and relationships, research on model generation with Alloy has been very active. Anastasakis et al. (2010) discussed how to translate a UML class diagram into Alloy. They proposed some rules to map the UML class diagram and the limited OCL constraints onto Alloy Language. Sen et al. (2008) proposed a tool called Cartier to generate test models for testing model transformations. McQuillan and Power (2008) proposed a metamodel for the measurement of object-oriented systems. Users can define some metrics for an object-oriented system using this metamodel, and then the metrics are translated into Alloy to generate a valid model.

ECL^{i}PS^e, proposed by Apt and Wallace (2007), is a model constraint solver. Cabot et al. (2008) proposed an approach to translating a UML model with OCL constraints into ECL^{i}PS^e. Their approach is supported by the tool EMFtoCSP Pérez et al. (2012). And, it has been applied to test model generation González et al., 2012).

Soeken et al. (2010, 2011) also proposed an approach to verify a UML model with OCL constraints using a SAT solver. They employed bit-vector theory to encode the metamodel and the constraints.

It is not difficult to find that solver-based approaches are more flexible because they can deal with more kinds of declarative and semantic constraints. They are suitable for model verification and white-box testing. However, they cannot generate large models efficiently, compared to our algorithm-based approaches. Hence, they are less suitable to handle performance testing of model-related operations.

Algorithm-based paradigm. Mougenot et al. (2009) proposed a uniform generator of huge models based on Boltzmann method Duchon et al. (2004). They translated a metamodel into a tree specification, where classes were nodes and containment references were edges. During the translation, multiplicities of containment references are also considered. Then, they employed Boltzmann method to generate a valid tree conforming to the specification. Their approach is quiet efficient. However, they did not discuss how to generate non-containment references. Semantic constraints are also neglected in their approach. So their approach might produce an invalid model, e.g., a class diagram containing an inheritance circle.

Brottier et al. (2006) also proposed an algorithm of model generation for testing model transformations. Their algorithm builds a model according to certain coverage criteria by combining a set of model fragments. However, they did not discuss how to create those fragments.

Ehrig et al. (2009) introduced a graph-grammar-based model generation approach. In their approach, metamodels and constraints are encoded as a set of graph transformation rules. By executing those rules, a model can be generated. Even though graph-grammar based approach is also declarative syntactically, we do not adopt it because the most frequently-performed operation during graph transformation is *graph pattern matching*, which has been proven to be an NP-complete problem in theory and is the performance bottleneck to generate large model efficiently. On the contrary, ours is more *configurable* and takes more constraints (such as semantic constraints) into account.

Preliminary study. Our preliminary study on the random model generation algorithm has been reported in our earlier paper He et al. (2014) published in COMPSAC'14. In the earlier paper, the basic ideas of the generation algorithm, as well as some experiment results, were presented. This paper, as an enhancement of our earlier, proposed a performance testing framework for model-related operations. The framework, based on a test model, provides the ability of specifying, managing, and performing test cases. The model generation algorithm is also integrated into the framework to produce test data. This paper also refined the model generation algorithm and discussed the procedure of model fixing in detail. At last, more case studies and experiments were presented in Section 5 compared to the earlier paper.

8. Conclusion and future work

Since the scalability of the model-related operation gained lots of attentions, testing its performance has become a vital task in the model-driven engineering. The paper contributes to this field in the following three aspects:

1. An extensible performance testing framework and a test model, which enable us to specify and organize test cases, and to carry out automated performance test;
2. A model generation algorithm, which can help us generate random inputs, used for eliminate the average time cost, efficiently and correctly;
3. Two case studies, one experiment in randomness, and two experiments in generation efficiency, which demonstrated the feasibility of our testing framework, and evaluated the randomness and the efficiency of our model generation algorithm.

In the future, we will try to handle more kinds of constraints (especially more semantic constraints) in model generation. Then, we will study if our model generation algorithm can produce models with restrictions, e.g., the process model that must be structural, as mentioned in Section 6, and will investigate to what extent our approach can overcome this limitation. Third, we will try to improve the usability of our prototype tool. Fourth, we will carry out more case studies and experiments to quantify how much our approach is better than others. At last, we plan to investigate whether the framework and the generation algorithm are suitable for black-box testing of model-related operations or not, owning to the white-box testing technology for some operations may not be available at present.

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Appendix

Algorithm 11 shows how to do the translation. Given a *Bound bound, Flatten*(*bound*, 1) returns the logic form.

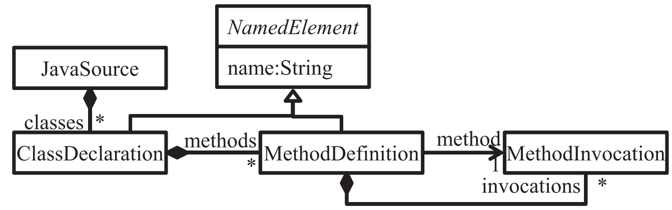

Fig. 12. JavaSource metamodel.

The metamodel of JavaSource is depicted as Fig. 12. It is directly extracted from the ATL transformation JavaSource2Table downloaded from the ATL Zoo.

Algorithm 11: Flatten(item, dPos)

Input: *item*, the item to be flattened; *dPos*, the default possibility
Output: the logic form of *item*

switch *type of item* **do**
  case *item is a literal*
    return $\{(literal, dPos)\}$;
  case *item is a bList*
    $pbi \leftarrow \{e | e \in item \wedge e$ is a pbItem $\}$;
    $aPos \leftarrow (1 - \sum_{e\in pbi} e.probability)/|item|$;
    return $\bigcup_{e\in pbi}$Flatten$(e, e.probability \cdot dPos)$ $+\bigcup_{e\in item-pbi}$Flatten$(e, aPos \cdot dPos)$;
  case *item is a bRange*
    $aPos \leftarrow 1/|item|$;
    return $\bigcup_{e\in item}$Flatten$(e, aPos \cdot dPos)$;

Algorithm 12: FixingModelForCase1'(r, e_t)

Input: e_t, a candidate target element; r, a reference to be initialized

$S \leftarrow$ the set of references being focused on;
$E \leftarrow$ the set of elements in the model;
$L \leftarrow$ the set of relationship in the model;
$cons \leftarrow$ the relationship constraint on S;
foreach $\langle e_x, e_y\rangle \in_S$ *the model* **do**
  if $\neg IsForbidden(S, e_x, e_t, cons.reflexive, cons.ordered)$, *and* $IsSrcCandidate(r, e_x, cons.tarUnique, cons.tarNecessary)$, *provided that* $\langle e_x, e_y\rangle$ *is removed* **then**
    foreach $e_z \in E$ *and* $r' \in S$ **do**
      if $\neg IsForbidden(S, e_z, e_y, cons.reflexive, cons.ordered)$ *and* $IsSrcCandidate(r', e_z, cons.tarUnique, cons.tarNecessary)$ *and* $IsTarCandidate(r', e_y, cons.srcUnique, cons.srcNecessary)$, *provided that* $\langle e_x, e_y\rangle$ *was removed* **then**
        if *type constraints are satisfied* **then**
          $L \leftarrow L - \langle e_x, e_y\rangle + \{\langle e_x, e_t\rangle, \langle e_z, e_y\rangle\}$, where $\langle e_x, e_t\rangle$ is a r-relationship and $\langle e_z, e_y\rangle$ a r'-relationship;
          return;

mark e_t as an invalid target of r;

Algorithm 13: FixingModelForCase2'(r, e_r)

Input: e_t, a candidate target element; r, a reference to be initialized

$E \leftarrow$ the set of elements in the model;
$L \leftarrow$ the set of relationship in the model;
$S \leftarrow$ the set of references being focused on;
$cons \leftarrow$ the relationship constraint on S;
foreach $e_u \in E$ **do**
  if *there exist* $e_x, e_y, e_z \in E$ *and* $r' \in S$ *that* $e_t \rightsquigarrow_S e_x$, $\langle e_x, e_y \rangle \in_S L$, *and* $e_y \rightsquigarrow_S e_z$ *hold* **then**
    if $IsSrcCandidate(r, e_z, cons.tarUnique, cons.tar.Necessary)$ *and* $IsTarCandidate(r', e_y, cons.srcUnique, cons.srcNecessary)$ *and* $IsSrcCandidate(r', e_u, cons.tarUnique, cons.tarNecessary)$ *and* $\neg IsForbidden(S, e_u, e_y, cons.reflexive, cons.ordered)$, *provided that* $\langle e_x, e_y \rangle$ *was removed* **then**
      if *the type constraints are satisfied* **then**
        $L \leftarrow L - \langle e_x, e_y \rangle + \{\langle e_u, e_y \rangle, \langle e_z, e_t \rangle\}$, where $\langle e_u, e_y \rangle$ is a r'-relationship and $\langle e_z, e_t \rangle$ a r-relationship;
        return;
mark e_t as an invalid source of r;

References

Anastasakis, K., Bordbar, B., Georg, G., Ray, I., 2010. On challenges of model transformation from UML to Alloy. Softw. Syst. Model. 9 (1), 69–86.
Apt, K.R., Wallace, M., 2007. Constraint Logic Programming using ECLiPSe. Cambridge University Press, New York.
Baudry, B., Ghosh, S., Fleurey, F., France, R., Le Traon, Y., Mottu, J.-M., 2010. Barriers to systematic model transformation testing. Commun. ACM 53 (6), 139–143.
Brottier, E., Fleurey, F., Steel, J., Baudry, B., Le Traon, Y., 2006. Metamodel-based test generation for model transformations: an algorithm and a tool. In: Software Reliability Engineering, 2006. ISSRE'06. 17th International Symposium on. IEEE, pp. 85–94.
Cabot, J., Clarisó, R., Riera, D., 2008. Verification of UML/OCL class diagrams using constraint programming. In: Software Testing Verification and Validation Workshop, 2008. ICSTW'08. IEEE International Conference on. IEEE, pp. 73–80.
Duchon, P., Flajolet, P., Louchard, G., Schaeffer, G., et al., 2004. Boltzmann samplers for the random generation of combinatorial structures. Comb. Probab. Comput. 13 (4-5), 577–625.
Ehrig, K., Küster, J.M., Taentzer, G., 2009. Generating instance models from meta models. Softw. Syst. Model. 8 (4), 479–500.
Finot, O., Mottu, J.-M., Suny, G., Attiogb, C., 2013. Partial test oracle in model transformation testing. In: Duddy, K., Kappel, G. (Eds.), Theory and Practice of Model Transformations. In: Lecture Notes in Computer Science, vol. 7909. Springer, Berlin Heidelberg, pp. 189–204.
Giner, P., Pelechano, V., 2009. Test-driven development of model transformations. In: Schrr, A., Selic, B. (Eds.), Model Driven Engineering Languages and Systems. In: Lecture Notes in Computer Science, vol. 5795. Springer, Berlin Heidelberg, pp. 748–752.
González, C.A., Cabot, J., 2012. Atltest: a white-box test generation approach for ATLl transformations. In: Model Driven Engineering Languages and Systems. Springer, pp. 449–464.
Guerra, E., Soeken, M., 2013. Specification-driven model transformation testing. Springer, Berlin Heidelberg, pp. 1–22.
He, X., Zhang, T., Ma, Z., Shao, W., 2014. Randomized model generation for performance testing of model transformations. In: 38th Annual International Computer Software and Applications Conference (COMPSAC'14). IEEE, pp. 11–20.
Jackson, D., Schechter, I., Shlyakhter, I., 2000. Alcoa: the alloy constraint analyzer. In: Software Engineering, 2000. Proceedings of the 2000 International Conference on. IEEE, pp. 730–733.
Küster, J.M., Gschwind, T., Zimmermann, O., 2009. Incremental development of model transformation chains using automated testing. In: Model Driven Engineering Languages and Systems. Springer, Berlin, Heidelberg, pp. 733–747.
McQuillan, J.A., Power, J.F., 2008. A metamodel for the measurement of object-oriented systems: an analysis using alloy. In: Software Testing, Verification, and Validation, 2008 1st International Conference on. IEEE, pp. 288–297.
Mougenot, A., Darrasse, A., Blanc, X., Soria, M., 2009. Uniform random generation of huge metamodel instances. In: Model Driven Architecture-Foundations and Applications. Springer, Berlin, Heidelberg, pp. 130–145.
Object Management Group, 2011. OMG Meta Object Facility (MOF) Core Specification Version 2.4.1.
Object Management Group, 2012. OMG Object Constraint Language (OCL) Specification Version 2.3.1.
Pérez, C.A.G., Buettner, F., Clarisó, R., Cabot, J., et al., 2012. Emftocsp: a tool for the lightweight verification of EMF models. Formal Methods in Software Engineering: Rigorous and Agile Approaches (FormSERA).
Sen, S., Baudry, B., Mottu, J.-M., 2008. On combining multi-formalism knowledge to select models for model transformation testing. In: Software Testing, Verification, and Validation, 2008 1st International Conference on. IEEE, pp. 328–337.
Shelburg, J., Kessentini, M., Tauritz, D., 2013. Regression testing for model transformations: a multi-objective approach. In: Ruhe, G., Zhang, Y. (Eds.), Search Based Software Engineering. In: Lecture Notes in Computer Science, vol. 8084. Springer, Berlin Heidelberg, pp. 209–223.
Soeken, M., Wille, R., Drechsler, R., 2011. Encoding ocl data types for sat-based verification of UML/OCL models. In: Tests and Proofs. Springer, Berlin, Heidelberg, pp. 152–170.
Soeken, M., Wille, R., Kuhlmann, M., Gogolla, M., Drechsler, R., 2010. Verifying UML/OCL models using boolean satisfiability. In: Proceedings of the Conference on Design, Automation and Test in Europe. European Design and Automation Association, pp. 1341–1344.
Song, H., Huang, G., Chauvel, F., Xiong, Y., Hu, Z., Sun, Y., Mei, H., 2011. Supporting runtime software architecture: a bidirectional-transformation-based approach. J. Syst. Softw. 84 (5), 711–723.
Van Amstel, M., Bosems, S., Kurtev, I., Pires, L.F., 2011. Performance in model transformations: experiments with ATL and QVT. In: Theory and Practice of Model Transformations. Springer, Berlin, Heidelberg, pp. 198–212.
Van Amstel, M.F., Van Den Brand, M.G., 2011. Model transformation analysis: staying ahead of the maintenance nightmare. In: Theory and Practice of Model Transformations. Springer, pp. 108–122.
Wu, H., Monahan, R., Power, J.F., 2012. Metamodel instance generation: a systematic literature review. Softw. Eng.. arXiv preprint arXiv:1211.6322.

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