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Towards Variability Management In Bidirectional Model Transformation

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***Abstract*—The bidirectional model transformation (BX) comprises a forward transformation *get* and a backward transformation *put*. Given that *get* may be an information-loss transformation, the behavior of *put* may be uncertain. An uncertain *put* produces many valid outputs that fit different application scenarios. This paper proposes an approach to variability management in BX to enable *put* to generate an output model with several *variation points* that can be configured to adapt this output for different uses. Firstly, this paper proposes a variability metamodel and management framework, which are used to characterize and configure variation points in a transformation result model. Secondly, this paper extends a BX language to specify a BX with variability. Thirdly, this paper presents a BX engine, which can execute a BX with variability and generate a model that contains variation points. Lastly, an evaluation is presented to show the feasibility and scalability of our approach.**

I. Introduction

In Model-Driven Engineering, there is an increasing need for model synchronization [1], [2], [3], [4] to support iterative, collaborative, and/or multi-view development, in which the models that are created at different development phases, by different developers and/or from different views of the same system, must be synchronized.

Bidirectional model transformation (BX) [5], [6], [7], [8] is a promising solution to model synchronization and has attracted many attentions from academia [9]. A BX can be defined either asymmetrically or symmetrically. Without losing generality, this paper adopts the asymmetric definition [10] that defines a BX as the following pair of functions:

$$get: \quad S \rightarrow V$$
$$put: \quad S \times V \rightarrow S$$

where, the forward transformation (get) produces a view model from a source model, and the backward transformation (put) converts the original source model and the updated view model into an updated source model. With regard to the symmetric case [6], we can combine two asymmetric BXs to realize a symmetric BX.

In practice, get can be an information-loss transformation, and consequently, the behavior of put becomes uncertain. Take the classic transformation `UMLtoRDBMS` [11] between UML Class Diagram and Relational Database Management System (RDBMS) model as an example. The forward transformation

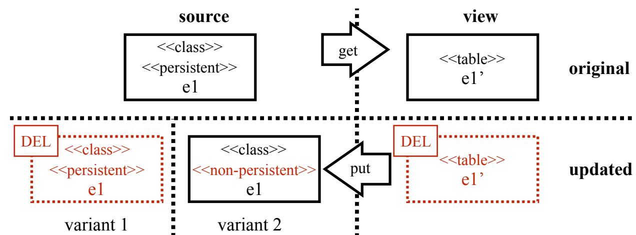

Fig. 1: Example of uncertainty

converts all persistent classes into tables. Nevertheless, as shown in Fig. 1, the deletion of a table may be propagated back to the Class Diagram at least in the following two ways: 1) deleting the class that corresponds to this table, or 2) changing the corresponding class into a non-persistent class.

These two variants of propagating the deletion of a table, as in Fig. 1, may be applied in different scenarios. Consider the following example scenarios: 1) Scenario 1 adopts variant 1 that deletes all the classes whose counterparts are deleted; 2) Scenario 2 adopts variant 2 that changes all the classes whose counterparts are deleted into non-persistent classes; And 3) scenario 3 combines variants 1 and 2 that delete some of the classes, whose counterparts are deleted, while convert the rest into non-persistent classes.

Intuitively, we can develop three separate BXs to cover the above three scenarios. Nevertheless, this solution suffers from high development costs and poor maintainability.

In conventional software engineering, the concept of *variability* has been proven in practice an effective technique that enables an application to be configured for use in different contexts [12]. This paper attempts to adapt software variability for (bidirectional) model transformation so that a *single* BX can be used in different scenarios.

This paper proposes *model transformation variability* by adapting software variability. *Transformation variability* can be defined at two different levels, namely, the specification and the instance levels, as follows:

- The specification-level variability is the ability of a transformation specification to be configured for use in a specific context, e.g., [13], [14].

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- The instance-level variability is the ability of the transformation output to be configured for use in a specific context, e.g., [15].

The specification-level variability implies that a transformation specification contains several variation points. We can change the behavior of this model transformation via configuring these variation points.

The instance-level variability means that a model transformation can produce a model that contains several variation points We can configure these variation points to adapt the output model for different uses.

This paper focuses on *the instance-level variability* within the context of *bidirectional model transformation*. Firstly, we propose a variability metamodel that is adapted from COVAMOF [16], a well-established conceptual model of software variability. Secondly, we extend our BX language and engine to support instance-level variability. The extended language and engine can declare and produce instance-level variation points during backward transformation. We also propose a variability management framework that is used to configure instance-level variation points in transformation output model.

There is another concept, called *ambiguity* that is similar to but different from *variability* discussed in this paper. Both ambiguity and variability originate from the nature of uncertainty. However, variability refers to *intentional*, useful, and controlled uncertain features in a BX, but ambiguity represents unintentional and uncontrolled features.

The rest of this paper is structured as follows: Section II introduces the basic concepts and presents the motivating example; Section III presents our approach to transformation variability management and demonstrates how to integrate the approach into bidirectional model transformation; Sections IV and V present our tool support and evaluation of our approach; Section VI discusses the related research efforts; The last section concludes the paper and the future work.

II. Background and Motivation

A. Bidirectional Model Transformation

A bidirectional model transformation converts a source model into a view model, and vice-versa. We can straightforwardly realize a BX using two separate unidirectional transformations. Such realization is difficult to assure the round-trip properties (discussed in Section III-D) of this BX, therefore systematical BX approaches that make BX easy and maintainable have been actively studied within the past decade.

There are three major systematical BX approaches, namely, the *relation*-based, *get*-based and *putback*-based.

Relation-based approaches (e.g., [3], [5], [7]) specify a BX as a set of bidirectional consistency relations between the source and view models. Afterwards, a pair of forward and backward transformations (get and put), which satisfies round-trip properties, is automatically derived from these consistency relations. *Get*-based approaches (e.g., [4]) specify a BX using a forward transformation (i.e., *get*), and then automatically derives the corresponding *put* from *get*. The *relation*-based and *get*-based approaches usually suffer from ambiguity problems [17], [10] that hinder developers from controlling the behavior of their BXs.

Putback-based bidirectional programming [10] has been proposed to tackle ambiguity problems. BiFluX [8], a *putback*-based BX language for XML, has been designed based on *putback*-based bidirectional programming. The key of a *putback*-based bidirectional programing is to describe how to update source model according to an updated view model. A *putback*-based BX is specified in the form of a backward transformation *put*. The *putback*-based BX is free from ambiguity problems because a unique *get* can always be derived from a well-defined *put* [10]. *Putback*-based bidirectional programming offers developers full control over the BX behavior.

We adapted BiFluX for bidirectional model transformation by combining BiFluX with OCL. Our language, which is the base of this paper, adopts the core language of BiFluX to interpret a BX over models, while OCL instead of XPath is used to specify the patterns and the expressions of models.

Listing 1: Example rule of *putback*-based BX

```
rule class2table(source p : Package, view s : Schema) {
 cn : String;
 update p:Package{classes=c:Class{name=cn, persistent=true,
    abstract=false}}
  with s:Schema{tables=t:Table{name=cn}} by
    match-> attribute2column(c, t)
    unmatchs-> delete c
  /* ALTERNATIVE:
    unmatchs-> enforce c:Class{persistent=false}
  */
    unmatchv-> enforce c:Class{name=cn,
      persistent=true, abstract=false}
}
```

Listing 1 shows a *putback* rule defined in our BX language, which specifies how to update a class using a table. The rule means that a persistent class c in the package p must be updated by a table t in the schema s, where the names of c and t must be identical. If such table t exists, then go on updating the attributes of c with the columns of t by calling the rule `attribute2column` (i.e., the `match` clause). If such table is missing, then delete class c in the result (i.e., the `unmatchs` clause). If such class is missing, then create a new class c (i.e., the `unmatchv` clause) and go on excuting the `match` clause. Assuming that we want to change class c into a non-persistent class when the corresponding table is missing, we replace the `unmatchs` clause with the *ALTERNATIVE* line of code in Listing 1.

B. Variability Management and COVAMOF

In COVAMOF [16], one of the major concepts is the *variation point*. Variation points are places in software artifacts that identify locations at which variation occurs [18]. Each variation point is associated with a set of *variants*. Each variant represents an alternative structure of the associated variation point. A variant may require or exclude other variants. Those types of dependencies among variants restrict variant selection.

The variability of a software artifact can be represented as a variability model that defines a set of variation points. Configuring a variability model is to select a variant for each variation point.

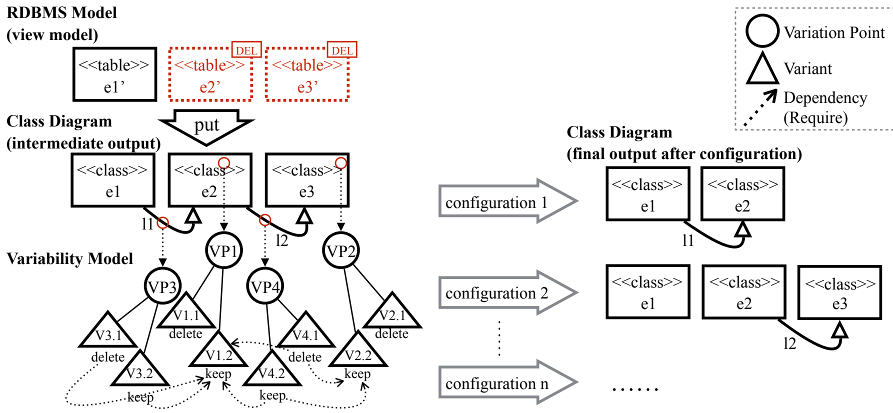


Fig. 2: Running example

C. Running Example

This paper uses the transformation `UMLtoRDBMS` mentioned in Section I as a motivating example. Assume that this BX ignores any information related to non-persistent classes. As shown in Fig. 1, the deletion of a table in the view model will result in a variation point in the updated source model with two variants.

Fig. 2 shows a more complex example of variability in this BX. Assume that the original source model contains three classes, namely, *e1*, *e2* and *e3*, where *e1* inherits from *e2* (i and *e2* inherits from *e3*. After the forward transformation, three tables, namely, *e1'*, *e2'* and *e3'* (consistent with their counterpart), are created in the view model, respectively.

Assume that tables *e2'* and *e3'* are deleted from the view model (the top-left part of Fig. 2). The deletion of these two tables will cause several variation points in the output of the backward transformation.

Firstly, consider how we can update classes *e2* and *e3*. Based on Fig. 1, *e2*/*e3* can be either deleted or converted into a non-persistent class. We identify two variation points, namely, `VP1` and `VP2`, for classes *e2* and *e3*, respectively. `VP1`/`VP2` has two variants, namely, `V1.1`/`V2.1` and `V1.2`/`V2.2`. `V1.1`/`V2.1` means deleting class *e2*/*e3*, while `V1.2`/`V2.2` means changing class *e2*/*e3* into a non-persistent one.

Inheritance relationship between *e1* and *e2* (called *l1*) and inheritance relationship between *e2* and *e3* (called *l2*), can also be updated in different ways, depending on how classes *e2* and *e3* are updated. We identify two variation points, namely, `VP3` and `VP4`, to represent how to update *l1* and *l2*, respectively. If *e2* is deleted, then *l1* and *l2* must be deleted by default. If *e3* is deleted, then *l2* must be deleted by default. If *e2* is preserved, then *l1* may be either deleted (i.e., variant `V3.1`) or preserved (i.e., variant `V3.2`). If *e2* and *e3* are both preserved, then *l2* may be either deleted (i.e., variant `V4.1`) or preserved (i.e., variant `V4.2`). Obviously, `V3.1` and `V3.2` depend on `V1.2`, and `V4.1` and `V4.2` depend on both `V1.2` and `V2.2`.

By using our variability metamodel proposed in Section III-B, the output of the backward transformation that is described above can be specified as the bottom-left part of Fig. 2. This output model comprises an intermediate output and a variability model that stores the variation points and variants existing in the intermediate output. We obtain different final output models that fit different needs by configuring the variability model in different ways, . As shown in the right part of Fig. 2, configuration 1 comprises `V1.2`, `V2.1` and `V3.2`, and configuration 2 comprises `V1.2`, `V2.2`, `V3.1` and `V4.2`.

III. Transformation Variability Management

A. Overview of Our Approach

Instance-level transformation variability is the ability of the transformation output to be configured for use in a specific context. A (bidirectional) model transformation must can produce an output model with variation points to support instance-level transformation variability.

We identify the following requirements of transformation variability management:

1) We must provide full control over transformation variability. Developers must can specify what types of variation points and variants exist. Take `UMLtoRDBMS` as an example. If developers regard variant 2 in Fig. 1 unnecessary, then they must can exclude this variant.
2) We must provide the support for managing dependencies among variation points and variants. As demonstrated in Section II-C, a variant may depend on other variants. Such dependency must can be specified, established, stored and validated.

This section proposes our instance-level transformation variability approach that fulfills the above two requirements. Fig. 3 shows the overview of our approach that comprises the following three major steps:

1) Developers define a variability-aware BX using our BX language.
2) The variability-aware BX is performed on our variability-aware BX engine. This engine captures variation points at runtime, and then produces an intermediate transformation output associated with a variability model. This transformation output is intermediate

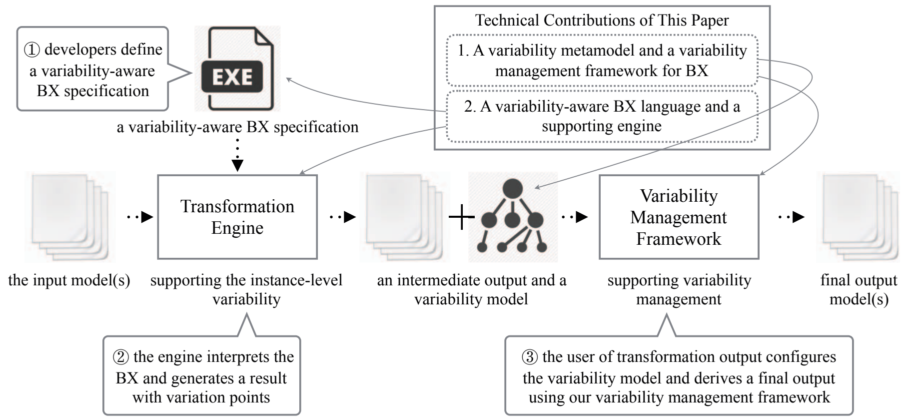


Fig. 3: Overview of our approach

because it contains variation points that are externally stored in the associated variability model as first-class elements. Developers turn the intermediate output into a final output after configuring all variation points.

3) The variability model (as well as the intermediate output) is loaded into our variability management framework. Afterwards, the user of the transformation output creates a configuration by selecting variants existing in the variability model. Lastly, the framework derives the final transformation output from the intermediate output according to this configuration.

Specifically, we propose 1) a variability metamodel and a management framework that are used to declare and configure variability models respectively, and 2) a variability-aware BX language and its engine, as a prototype implementation and a demonstration of integrating variability into BX.

B. Variability Metamodel and Framework

1) Metamodel: Firstly, we propose a variability metamodel that is adapted from COVAMOF [16] for BX to define a variability model that comprises several variation points and variants associated with a transformation output. This variability metamodel is shown in Fig. 4.

VariabilityModel represents the root element of a variability model. It comprises a list of *VariationPoints*, each of which represents a location in the intermediate transformation output to be further customized. It is also associated with one or more intermediate result *Models*, each of which will be replaced by an implementation-specific model artifact.

A *VariationPoint* is associated with a set of *Variants* each of which denotes an alternative of the *VariationPoint*. Within the context of BX, a *Variant* is defined as a sequence of *ModelOperations*. For instance, in our running example in Section II-C, `V1.1` is to *delete* the class *e2*, while `V1.2` is to *change* the class into a non-persistent one.

A *ModelOperation* specifies a modification to the intermediate transformation output. In this paper, we identify four

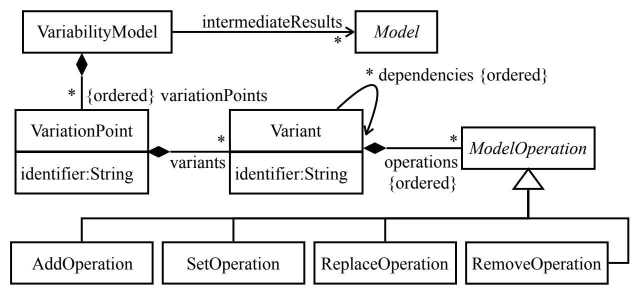


Fig. 4: Variability metamodel for BX

EMF[1]-specific operations as concrete subclasses of *ModelOperation*, namely, *AddOperation*, *SetOperation*, *ReplaceOperation* and *RemoveOperation*. These four operations are directly supported by EMF. In theory, they can be replaced by other model change operations, e.g., [20].

An *AddOperation* can add (or insert) a value into a multivalued feature (i.e., property or relationship) of a certain model element. A *SetOperation* can change the value of a feature of a model element. A *ReplaceOperation* can replace a model element within a collection with another element. A *RemoveOperation* is used to remove a value from a multivalued feature of a model element. For instance, `V1.1` in our running example can be realized by a *RemoveOperation*, while `V1.2` a *SetOperation*.

A *Variant* may depend on other *Variants*. It means that the selection of the dependent requires all the depended *Variants* to be selected. This relation, denoted by *dependencies* in our variability model, is simplified from the concept of *Dependency* in COVAMOF to fit the context of BX.

2) Framework: Using the variability metamodel, we can define a variability model that specifies variation points and variants in an intermediate transformation output (in our approach, this variability model is automatically generated by our

[1]Eclipse Modeling Framework, an open-source implementation of OMG's Meta Object Facility [19]. http://www.eclipse.org/modeling/emf/

engine). We present a transformation variability management framework to manage this variability model.

Our variability management framework has the following major functions: Firstly, it provides a configuration editor to users to configure a variability model that complies with the variability metamodel; Secondly, it can validate the configuration of the variability model; Thirdly, it can interpret a valid configuration and convert a intermediate output model into a final output that does not contain variation points.

Configuring a variability model is to select variants for all variation points. For a configuration that comprises a set of *Variants* selected, our variability management framework can determine whether this configuration is valid using the following validation rules:

Rule 1: For each *VariationPoint* vp, only one of its *Variants* can be selected, i.e.,

$$\forall vp(v_1, v_2 \in vp.variants \wedge v_1, v_2 \text{ are selected} \Rightarrow v_1 = v_2)$$

For instance, in our running example, `V1.1` or `V1.2` can be selected, but they cannot be selected meanwhile.

Rule 2: If *Variant* v is selected, then all *Variants* v depends on must also be selected because v requires all of them, i.e.,

$$\forall v\big(v \text{ is selected} \Rightarrow \forall v'(v' \in v.dependencies \wedge v' \text{ is selected})\big)$$

For example, if `V4.2` is selected, `V1.2` and `V2.2` must also be selected.

Rule 3: For each *VariationPoint* vp, at least one of its associated *Variants* that are selectable must be selected, i.e.,

$$\forall vp\big(S(vp) \neq \emptyset \Rightarrow \exists v(v \in S(vp) \wedge v \text{ is selected})\big)$$

where $S(vp) \equiv \{v | v \in vp.variants \wedge isSelectable(v)\}$. This rule means that all *VariationPoints* must be configured.

The function $isSelectable$ determines whether a *Variant* can be selected. *Variant* v is selectable iff none of its sibling *Variants* is selected and all *Variants* v depends on are selectable. $isSelectable(v)$ is defined as follows:

$$\begin{gathered}\forall v'(v, v' \in vp.variants \wedge v' \neq v \Rightarrow v' \text{ is not selected}) \\ \wedge \forall v''(v'' \in v.dependencies \Rightarrow isSelectable(v'') = true)\end{gathered}$$

When a configuration of a variability model is valid, our framework can interpret it by applying all *ModelOperations* that are associated with the selected *Variants* in this configuration to the intermediate output in a proper order to derive a final output model.

We define a partial order $\prec$ to determine the execution order of two *ModelOperations*. $o_1 \prec o_2$ means that o_1 must be executed before o_2. Assuming that two *ModelOperations* o_1 and o_2 are associated with two *Variants* v_1 and v_2 respectively, $\prec$ is defined as follows:

- If $v_1 = v_2 = v$ and $v.operations.indexOf(o_1) < v.operations.indexOf(o_2)$, then $o_1 \prec o_2$.
- If $v_1 \in v_2.dependencies$, then $o_1 \prec o_2$. Specifically, if v_2 depends on v_1, all operations associated with v_1 must be performed before the operations associated with v_2.
- Provided that $v_1 \in vp_1.variants$, $v_2 \in vp_2.variants$ and *VariationPoints* vp_1 and vp_2 belong to *VariabilityModel* vm, if $vm.variationPoints.indexOf(vp_1) > vm.variationPoints.indexOf(vp_2)$, then $o_1 \prec o_2$.

With the help of $\prec$, our framework interprets a configuration according to Algorithm 1.

Algorithm 1: Interpreting a configuration

Input: $conf$, a valid configuration; m_I, a intermediate transformation output model
Output: m_F, a final output model

$V = \{$all *Variants* selected in $conf\}$;
$O = \bigcup_{v_i \in V} \{o | o \text{ is a } \textit{ModelOperation} \text{ associated with } v_i\}$;
sort O using the order $\prec$;
$m_F =$ apply all *ModelOperations* in O successively to m_I;
return m_F;

C. Variability-Aware BX

We must extend a BX language and its execution engine for specifying and performing variability-aware BXs. We use our *putback*-based BX language and its engine introduced in Section II to demonstrate how to integrate instance-level variability into model transformation. We assume that *the same idea can also be applied to other transformation languages*.

1) Language: We proposes the following new types of statements to specify the instance-level variability, i.e., the `variable` and `maybe` statements:

`variable` [*identifier*] {*statement* + }
`maybe` [*identifier*] (`when` [*identifier*]+)? *statement*

A `variable` statement declares a scope with variability. Each execution of this statement will result in a *VariationPoint* in the intermediate output. A `variable` statement has an `identifier` expression, which is used to uniquely identify a *VariationPoint* in a variability model.

A `variable` statement comprises several `maybe` statements each of which declares a *Variant*. A `maybe` statement also has an `identifier` expression, which is used to uniquely identify a *Variant* within a *VariationPoint* created from the `variable` statement that contains this `maybe` statement. A `maybe` statement may own a `when` clause to specify what *Variants* this `maybe` statement depends on by using a list of `identifiers`.

Within a `variable` statement, all the model modification statements must be placed under a certain `maybe` statement. Thereby, our transformation engine can capture all the changes to the result model, and can record them in the *Variant* element created by the `maybe` statement.

Listing 2: Examples of variability declaration

```
variable['table deletion'+c] {
 maybe['delete'] delete c;
 maybe['keep'] enforce c:Class{persistent=false}
}
```

```
variable['super'+c+p] {
  maybe['remove'] when['table_deletion'+c+'keep']
    delete c.super=p;
  maybe['preserve'] when['table_deletion'+c+'keep'] {}
}
```

Listing 2 shows two `variable` statements. The first `variable` statement (lines 1 to 4) declares that how to propagate the deletion of a table to class c is a variation point (e.g., `VP1` and `VP2` in our running example). It comprises two `maybe` statements that denote two variants, i.e., deleting c (e.g., `V1.1` and `V2.1`) and changing c into a non-persistent one (e.g., `V1.2` and `V2.2`). Given that we must associate a variation point that is created by this `variable` statement with class c, the identifier expression of this `variable` statement is a concatenation of string “table deletion” and c. We can replace the `delete` statement in line 7 of Listing 1 (i.e., the `unmatchs` statement) with the first `variable` statement in Listing 2 to integrate this variability into the BX. Thereby, when a table is deleted, a *VariationPoint* will be created for the class corresponding to this table by executing this `variable` statement.

The second `variable` statement (lines 5 to 9) in Listing 2 declares a variation point about how to update the *super*-relationship between classes p and c (e.g., `VP3` in our running example), when the table corresponding to c has been deleted. Therefore, the identifier expression of this `variable` statement is a concatenation of string “super” and classes c and p. This `variable` statement comprises two `maybe` statements (lines 6 and 8) that denote two variants, i.e., deleting the relationship (e.g., `V3.1`) and preserving the relationship (e.g., `V3.2`), when c is not deleted. The two `maybe` statements depend on the second `maybe` statement in the first `variable` statement (line 3). Such dependency is specified by two `when` clauses, in which we combine the identifiers of the first `variable` statement and its second `maybe` statement (i.e., “table deletion”+c+“keep”).

2) Execution: We extend our bidirectional model transformation engine to support the proposed `variable` and `maybe` statements. We assume that the same idea can also be applied to other model transformation technologies.

During backward transformation, `variable` and `maybe` statements are executed to produce *VariationPoints* and *Variants*. A `variable` statement is performed based on Algorithm 2. Briefly, our engine creates a *VariationPoint* vp and pushes vp onto a stack of *VariationPoints*. Afterwards, the inner statements of the `variable` statement being executed (including all `maybe` statements) are executed.

A `maybe` statement is executed based on Algorithm 3. Firstly, our engine calculates the required *Variants* (lines 1 to 7) according to the `when` clause of the `maybe` statement being executed. If any required *Variant* is missing, then the engine will skip this `maybe` statement (line 4 and 5). Secondly, our engine creates and initialize a new *Variant* v (lines 8 to 13). Thirdly, our engine performs all *ModelOperations* that belong to the *Variants* recursively depended by v (lines 16 to 18). Afterwards, our engine executes all statements contained in this `maybe` statement and captures all model changes that happen during the execution of the inner statements (lines 19 to 21). Lastly, our engine undoes all *ModelOperations* in the reversed order and restores the runtime state (lines 22 to 24).

Take the first `variable` statement in Listing 2 as an example. When this `variable` statement is executed, its two `maybe` statements are executed successively. When the first `maybe` statement is executed, the class bound to c is deleted, and our engine creates a *RemoveOperation* for this change. Afterwards, the runtime state is restored, and then the second `maybe` statement is executed, resulting a new *Variant* with a *SetOperation* that changes the class bound to c into a non-persistent class. Finally, the runtime state is restored again and

Algorithm 2: executeVariableStatement(vs)

Input: vs, the `variable` statement to be executed

vp = new VariationPoint;
$variationPointStack.push(vp)$;
foreach *statement* s *included by* vs **do**
  execute s;
$variationPointStack.pop()$;

Algorithm 3: executeMaybeStatement(vs)

Input: ms, the `maybe` statement to be executed

1 $dvs = \emptyset$;
2 **foreach** *identifier expression* vi *in* `when` *clause of* vs **do**
3   dv = the *Variant*, previously created, whose identifier is equal to the value of vi;
4   **if** dv *is null* **then**
5   **return** ; `// skip this maybe statement`
6   **else**
7     $dvs.add(dv)$;
8 v = new Variant;
9 $v.identifier$ = the value of the identifier expression belonging to ms;
10 $rvs = \{x | x \in dvs \vee \exists y (y \in rvs \wedge x \in y.dependencies)\}$;
11 $v.dependencies = dvs \cup \{variantStack.top()\}$;
12 $vp = variationPointState.top()$;
13 $vp.variants.add(v)$;
14 copy current runtime state;
15 $variantStack.push(v)$;
16 $ops = \bigcup_{x \in rvs} x.operations$;
17 sort ops using the partial order $\prec$;
18 execute all *ModelOperations* in ops;
19 **foreach** *statement* s *included by* ms **do**
20   execute s and record all *ModelOperations* when s is being executed;
21 $v.operations$ = {all recorded *ModelOperations*};
22 undo all *ModelOperations* in $v.operations$ and ops;
23 $variantStack.pop()$;
24 restore runtime state;
25 **return**;

a *VariationPoint* with two *Variants* is produced.

During forward transformation, executing `variable` and `maybe` statements will cause a runtime exception because our approach does not support variability of forward transformation. Not supporting variability in the forward transformation can make it easier for developers to define a correct BX.

It is worthwhile to notice that in our approach, a variability-aware BX is still executed in a deterministic way, despite that it produces an output model with variation points.

D. Round-trip Property of BX with Variability

The most important BX properties are round-trip properties, i.e., the *GetPut* and *PutGet* laws. Without variability, round-trip properties are defined [10] as follows:

$$put\big(s, get(s)\big) = s \qquad \text{(GETPUT)}$$
$$get\big(put(s, v)\big) = v \qquad \text{(PUTGET)}$$

After integration of variability into BX, the backward transformation put returns a set of candidate outputs that can be derived from an intermediate output and a variability model. Therefore, put with variability can be characterized as follows (where $\mathcal{P}(S)$ is the power set of S):

$$put : S \times V \to \mathcal{P}(S)$$

Based on the new definition of put, the round-trip properties of a BX with variability are redefined as follows:

$$put\big(s, get(s)\big) = \{s\} \qquad \text{(GETPUT)}$$
$$\forall s'\big(s' \in put(s, v) \Rightarrow get(s') = v\big) \qquad \text{(PUTGET)}$$

The *GetPut* law says that the result of the backward transformation carried out immediately after the forward transformation should be equal to the original source model. The *PutGet* law says that for any candidate final result s' obtained by transforming a view model v in the backward direction, the result of converting s' in the forward direction should be equal to v. Currently, the developers must assure the round-trip property of the BX they defined. How to verify the round-trip property automatically is our future work.

IV. Tool Support

We have implemented a tool[2] support to BX variability, including our extended BX engine and a variability management tool. Fig. 5 presents a screenshot of our BX editor and variability management tool.

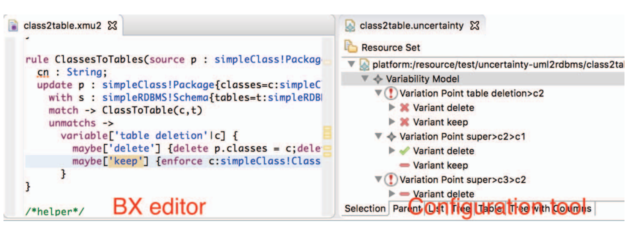


Fig. 5: Screenshot of tool support

[2]Source code is available at https://bitbucket.org/ustbmde/morel/wiki/Home

V. Evaluation

The objective of this section is to *evaluate* the *feasibility* and the *performance* of the proposed approach. The objective is further refined by the following two research questions: **RQ1:** *Can the proposed approach be used to handle the instance-level variability in BXs, which come from different application domains?* **RQ2:** *What is the performance loss incurred by the proposed approach, compared with the BXs without variability?* To answer **RQ1**, we make two variability-aware BXs having variability to demonstrate the feasibility of our approach. With regard to **RQ2**, we conduct an experiment in performance that compares these variability-aware BXs with corresponding BXs without variability, respectively.

A. UML to RDBMS

The first BX is `UMLtoRDBMS`, our running example. This BX is intended to demonstrate that our approach can support complex variant points and dependencies. We identify four types of variation points in total.

The first two types of variation points are about how to propagate the deletion of a table and how to update the *super*-relationships among classes. Given that they have been presented in Listing 2 and explained in Section III-C, this section omits their details.

The third type of variation points is about converting a column of a table back to an attribute of a class. Given a column cl in a table t and a class c corresponding to t, assume that we cannot find an attribute in class c that corresponds to cl. To convert cl, we must determine whether cl can match any attribute inherited from any superclass of c. Due to the influence of the first two types of variation points, we have several possible strategies of converting cl as follows: starting from each direct superclass sc of c,

- if sc is a persistent class and contains an attribute which matches cl, then return (this is the default update strategy rather than a *Variant*);
- if sc is or is changed into a non-persistent class and the inheritance from c to sc is preserved, go on searching in superclasses of sc;
- otherwise, stop searching, and then create a new attribute that matches cl in c.

The last two cases can be specified as Listing 3. Lines 2 and 3 specify the second case, and lines 4 and 5 the third case. Notice that in Listing 3, we specify dependencies among *Variants* using `when` clauses.

Listing 3: Variation point of updating super attributes

```
variable['update_super_attribute'+c+sc+cl.name] {
 maybe['go_on'] when['super'+c+sc+'keep']
   ... /* go on searching in the superclasses of sc */
 maybe['stop'] when['super'+c+sc+'delete']
   enforce c:Class{attributes=a:Attribute{name=cl.name}}
}
```

The fourth type of variation points is about how to propagate the deletion of a foreign key back to an association in Class Diagram. In `UMLtoRDBMS`, a foreign key fk, which connects two tables, is transformed from an association $assoc$, which

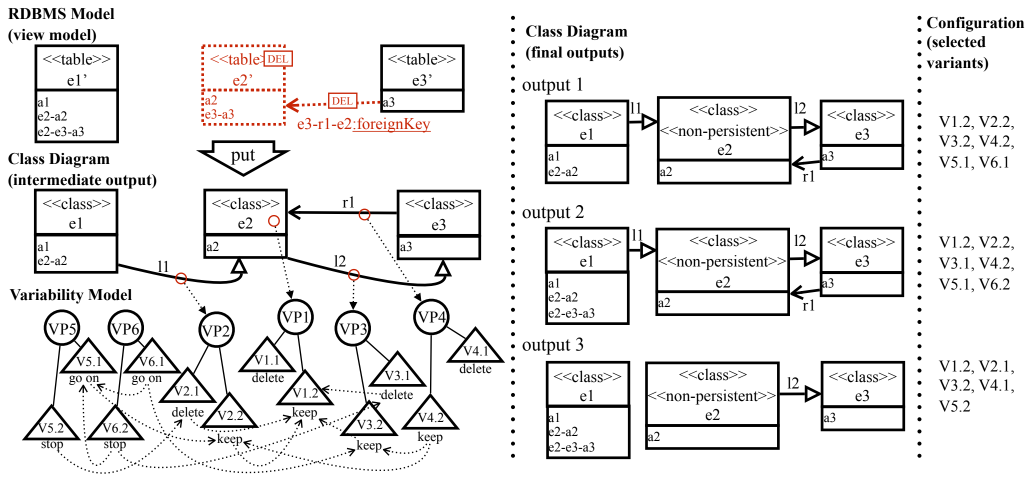


Fig. 6: Example of UMLtoRDBMS

connects two classes. If only fk is deleted while the associated tables are preserved, then delete $assoc$. If fk and at least one of the associated tables (e.g., t) are deleted, there are two variants as follows: 1) delete $assoc$; 2) when the class tc that corresponds to t is changed into a non-persistent class, then preserve $assoc$ because this BX does not convert any information related to non-persistent classes, as mentioned in Section II-C. The two variants are encoded as Listing 4:

Listing 4: Variation point of updating associations

```
variable['deletion_of_foreign_key'+sc+tc+an] {
  maybe['delete'] delete assoc;
  maybe['keep'] when['table_deletion'+tc+'keep'] {}
}
```

Fig. 6 shows an example that contains all types of variation points. In the original source model, there are three classes, namely, *e1* to *e3*, and an association *r1* from *e3* to *e2*. *e1*, *e2* and *e3* have three attributes *a1*, *a2* and *a3*, respectively. Besides, *e1* inherits from *e2*, and *e2* inherits from *e3*. The original source model results in a view model that contains three tables and a foreign key (called *e3-r1-e2*).

Assume that both table *e2* and foreign key *e3-r1-e2* are deleted. The backward transformation generates an intermediate output and a variability model as shown in the bottom left part of Fig. 6. `VP1`, `VP2` and `VP3` in Fig. 6 are similar to `VP1`, `VP3` and `VP4` in Fig. 2, respectively. `VP4` denotes the variation point about how to update *r1*, which is created according to Listing 4. `VP5` and `VP6` denote the variation points about how to convert column *e2-e3-a3* back to an attribute in class *e1*, which is created according to Listing 3.

`V5.1`, which depends on `V2.2`, represents the case that *l1* is preserved; `V5.2`, which depends on `V2.1`, represents the case that *l2* is deleted. `V6.1`, which depends on `V5.1` and `V3.2`, represents the case that both *l1* and *l2* are preserved; `V6.2`, which depends on `V5.1` and `V3.1`, represents the case that *l1* is preserved and *l2* is deleted.

The middle part of Fig. 6 shows several final output models derived from the intermediate model and the variability model, and the rightmost part of Fig. 6 shows the corresponding configurations. For example, result 3 is derived from `V1.1`, `V2.1`, `V3.2`, `V4.1` and `V5.2`.

B. Hierarchical Statechart to Flat Statechart

The BX between a hierarchical statechart (HSM) and a flat statechart (FSM), which was studied by Eramo et al. [15], also has variability. This example is used to demonstrate that our approach can handle the BX studied by others.

In brief, the forward transformation converts a HSM (i.e., a statechart owning composite states) into a FSM (i.e., a statechart without composite states). A top-level state *s* in a HSM will be converted into a state *s'* in a FSM. A transition that starts from or ends with a top-level state *s* or an inner state of *s* will be converted into a transition that starts from or ends with a state *s'* in the FSM. Besides, the transitions within a composite state will be ignored.

A variability issue arises during the backward transformation when a transition is created from or to a state in a FSM that corresponding to a composite state *s* owning inner states in the HSM: *s* and any inner state of *s* can be the source or target of tis transition in the HSM.

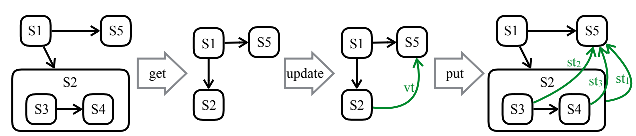


Fig. 7: Example of HSMtoFSM

As shown in Fig. 7, a new transition *vt* is created from *S2* to *S5* in the view model. In the updated source model, the corresponding transition *st* can be inserted from *S2*, *S3* or *S4*, to *S5*. To handle this variability, Listing. 5 specifies how to connect the source and target of a transition using two `variable` statements. They imply that the source/target of the transition can be the top-level state *s* or any of the inner states of *s* obtained by iterating `eAllContents` of *s*.

Listing 5: Variation point declaration in HSMtoFSM

```
variable['source'+vt] {
  maybe['to'+s] enforce st:hsm!Transition{source=s};
  foreach s:hsm!CompositeState{eAllContents=inner:hsm!State{}}
    ->maybe['to'+inner] enforce st:hsm!Transition{source=inner}
}}
variable['target'+vt] {
  maybe['to'+s] enforce st:hsm!Transition{target=s};
  foreach s:hsm!CompositeState{eAllContents=inner:hsm!State{}}
    ->maybe['to'+inner] enforce st:hsm!Transition{target=inner}
}}
```

The approach of Eramo et al. generates all possible final output models automatically by using constraint solving. Developers cannot design the variability of a BX, specifically, they cannot precisely specify what particular variation points and variants this BX has. Compared with Eramo's approach, our approach provide more control over BX variability without losing the processing ability of transformation variability.

C. Performance Loss

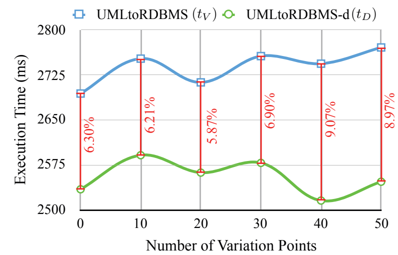
To evaluate the impact on performance of our approach, we compare the execution time t_V of a BX having variability with the time t_D of the same BX without variability. Then, we calculate the performance loss incurred by our approach, which is calculated as

$$(t_V - t_D)/t_D$$

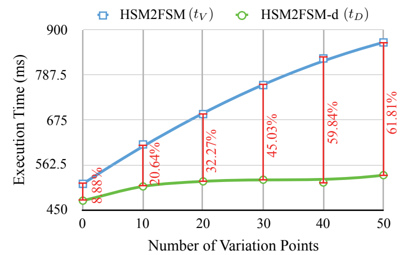
Subject BXs. We use the two BXs (i.e., UMLtoRDBMS and HSMtoFSM) presented in Sections V-A and V-B as the subjects to be studied. The control groups are derived from the subject BXs, as follows: 1) for UMLtoRDBMS, a BX (called UMLtoRDBMS-d), which always removes the class when the table is deleted in the view model, is developed; 2) for HSMtoFSM, a BX (called HSMtoFSM-d), which always connects the new transition with top-level states, is developed.

Process. The experiment is conducted on a MacBook Pro with an Intel Core i7 2.8Ghz processor and 16Gb RAM. For each BX as well as its control group, we use a random model generator [21] to generate an original source model. Then, we execute the forward transformation, and obtain a view model. After that, we create a set of modified view models, which result in different numbers of variation points (i.e., 0, 10, 20, 30, 40, and 50 variation points). For UMLtoRDBMS, the original source model contains 1000 model elements (i.e., 300 classes, 600 attributes, and 100 associations). The updated view models are created by renaming tables repeatedly. For HSMtoFSM, the original source model also contains 1000 model elements (i.e., 100 composite states, 350 states, and 550 transitions). The updated view models are created by renaming transitions repeatedly. Renaming an element will be recognized by the BXs as an element insertion following a deletion, and will not change the size of the view model. Finally, we execute the backward transformations, including the subject BX and its control group, and capture the average execution times (excluding I/O).

Results. The result of case UMLtoRDBMS is shown in Fig. 8a. Since the size of the view model is constant, the execution times of UMLtoRDBMS and UMLtoRDBMS-d did not vary a lot. The performance loss ranged from 5.87% to 9.07%, which



(a) Result of UMLtoRDBMS



(b) Result of HSMtoFSM

Fig. 8: Results of experiment in performance loss

is acceptable. The result of case HSMtoFSM is shown in Fig. 8b. The execution times of HSMtoFSM-d increased slightly. However, the execution times of HSMtoFSM increased linearly with the number of variation points, and the performance loss increased (almost linearly) from 8.88% to 61.81%. It is because HSMtoFSM has to traverse all the inner states of top-level composite states, while HSMtoFSM-d does not. Hence, the more variation points there are, the more inner states HSMtoFSM visited, and consequently, the more performance loss is incurred. Overall, this experiment shows that the performance loss incurred by our approach is reasonable.

D. Threats to Validity

The first threat to validity is the choice of the two example BXs studied, which are relatively simple. However, they are sufficient to demonstrate the feasibility and the usage of our approach. The second threat to validity is the complexity of the test input models. In the future, we plan to conduct more experiments to validate the scalability of our approach to mitigate this threat.

VI. Related Work

Variability management in model transformation has been discussed from both the theoretical and the solution aspect. From the theoretical aspect, Stevens [17] analyzed the uncertainty issue, which may result in variability in practice, in the context of bidirectional transformation; Diskin et al. [22] proposed a formal framework of delta-lens supporting uncertainty. They both can be used as a guide to the development of concrete solutions.

Concrete solutions to variability management in (bidirectional) model transformation can be roughly divided into two groups: the specification-level and the instance-level, as discussed in Section I. Strüber et al. [14] proposed a specification-level approach to variability-based model transformation. Their approach enables developers to define a model transformation containing variation points. Given a valid configuration, a classical transformation that has no variation point can be derived. To facilitate defining variability-based transformations, they also proposed a rule merging algorithm [13]. Salay et al. [23] also proposed an approach that lifts model transformation to product lines. However, their approach is designed for the variability in input models.

As for the instance-level solutions, Eramo et al. [15] proposed a metamodel-based approach. The basic idea of their approach is to automatically derive an uncertainty metamodel from the metamodel used by a BX. Afterwards, they encode this BX and uncertainty metamodel into a constraint solving problem. Therefore, a constraint solver can find all models each of which conforms to the uncertainty metamodel and represents a variant output of the BX. However, they did not discuss how to support dependencies among variants. The constraint-solving-based BX approach, proposed by Macedo et al. [7], also has the potential to support the instance-level variability by asking the solver to find all possible result models. However, this kind of approach may not be scalable when there are a lot of variation points. Our approach, which is also an instance-level approach, differs from the above approaches. Instead of asking a solver to explore the search space freely, our approach provides developers with full control over their BXs. Developers can explicitly specify what types of variation points, variants and dependencies may exist in the BX output, and how to produce them.

VII. Conclusion and Future Work

The major contributions of this paper are summarized as follows: 1) a variability metamodel and management framework for model transformation; 2) a BX language and an engine as a demonstration to support the definition and execution of a BX with variability; 3) two examples of BXs with variability that illustrated the feasibility of the proposed approach.

In the future, we plan to explore how to use our approach to support the specification-level variability. Besides, during our evaluation, we observed that many human efforts were required to configure the variability model when there were a number of variation points. Although our tool support can check, filter and highlight available variants to ease the configuration, we assume that more the usability of our tool can be further enhanced. Lastly, more case studies and experiments will be conducted to evaluate our approach.

Acknowledgement

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