SuperMod — A Model-Driven Tool that Combines Version Control and Software Product Line Engineering

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Abstract: Version control (VC) and Software Product Line Engineering (SPLE) are two software engineering disciplines to manage variability in time and variability in space. In this paper, a thorough comparison of VC and SPLE is provided, showing that both disciplines imply a number of desirable properties. As a proof of concept for the combination of VC and SPLE, we present SuperMod, a tool realizes an existing conceptual framework that transfers the iterative VC editing model to SPLE. The tool allows to develop a software product line in a single-version workspace step by step, while variability management is completely automated. It offers familiar version control metaphors such as check-out and commit, and in addition uses the SPLE concepts of feature models and feature configuration the definition of logical variability and to define the logical scope of a change. SuperMod has been implemented in a model-driven way and primarily targets EMF models as software artifacts. We successfully apply the tool to a standard SPLE example.

1 INTRODUCTION

Version control (*VC*) has become indispensable for software engineers to control software evolution and to coordinate changes among a team. Version control systems (*VCS*) such as *Git* (Chacon, 2009) or Subversion (Collins-Sussman et al., 2004) propose an iterative three-stage editing model (cf., Figure 1): (1) A developer *checks out* a revision of a software project from a *repository*. A copy of the project is created in the local *workspace*. (2) In the workspace, the developer *modifies* the project by implementing new functionality or by fixing bugs. (3) To make these modifications visible to others, the developer *commits* his/her changes to the repository. For the internal representation of version differences within the repository, two distinct approaches exist. *Symmetric deltas* (Rochkind, 1975) comprise a *superimposition* of all existing revisions, assigning *version identifiers* to each element. Using *directed deltas* (Tichy, 1985), *change sequences* reconstruct product revisions on demand, ensuing form a *baseline* revision, which is fully persisted.

Software Product Line Engineering (*SPLE*) aims at a systematic development of a family of software products by exploiting the variability among members thereof (Clements and Northrop, 2001; Pohl et al., 2005). Core assets of different products are provided as a *platform*. Commonalities and differences among products are captured in *variability models*, e.g., *feature models* (Kang et al., 1990). In literature, a two-stage SPLE process is proposed (cf., Figure 2): (1) During *domain engineering*, platform and variability model are defined. A *mapping*, e.g., *presence condi-*

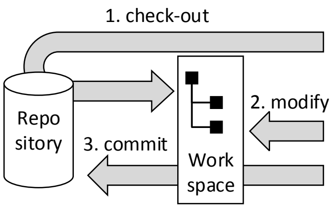

Figure 1: The iterative three-stage editing model proposed by version control systems.

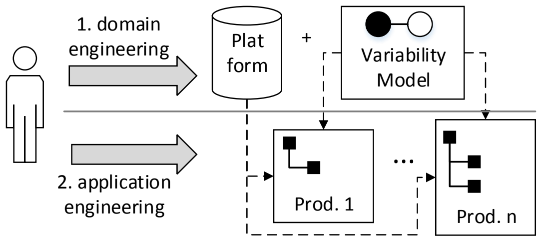

Figure 2: The usual two-stage SPLE process.

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tions (Czarnecki and Kim, 2005), specifies which part of the platform realizes which feature(s). (2) In *application engineering*, variability is resolved, e.g., by specification of a *feature configuration*, and a product with the desired features is derived in a preferably automated way. For the definition of the platform, two distinct approaches exist: Using *positive variability*, a common *core* is defined to which specific features may be added, e.g. by *composition* (Apel and Kästner, 2009). *Negative variability* means to specify the platform as *superimposition* of product variants, from which elements must be removed to obtain a specific product. This is realized, e.g., by *preprocessor languages* (Kästner et al., 2008).

Model-Driven Software Engineering (*MDSE*) (Völter et al., 2006) considers *models* as first-class artifacts, using well-defined languages such as the *Unified Modeling Language* (*UML*) (OMG, 2011). Many model-driven applications are built upon the *Eclipse Modeling Framework* (EMF) (Steinberg et al., 2009). The combination of MDSE with VC or SPLE is subject to many research activities, resulting in the integrating disciplines *Model Version Control* (Altmanninger et al., 2009) and *Model-Driven Product Line Engineering* (*MDPLE*) (Gomaa, 2004), which promise increased productivity by raising the abstraction level of the artifacts subject to variability.

In (Schwägerl et al., 2015), we have elaborated a *conceptual framework* for the integration of MDPLE, SPLE, and VC. The framework addresses the incremental development of a model-driven software product line in a single-version workspace using a filtered editing model that fully automates variability management. In addition to a revision graph, which describes the evolution of the product, a feature model and feature configurations are used to express logical variability and to define the logical scope of a change.

The current paper presents *SuperMod*, a model-driven *tool* that realizes the conceptual framework in order to integrate temporal and logical versioning. The tool allows to develop a software product line in a single-version workspace step by step using the familiar version control metaphors *update* and *commit*. The product line may contain arbitrary model and non-model artifacts. The feature model plays a dual role, being subject to evolution and providing an additional (logical) variability model for the product line. Our integrated solution significantly reduces the versioning overhead, since a manual mapping of product line artifacts becomes unnecessary. The tool integrates well with existing Eclipse editors.

The paper is structured as follows: After introducing a motivating example, a comparison of VC and SPLE concepts is performed in Section 3. Next, in Section 4, the implementation and user interface of SuperMod are sketched and the operations *check-out* and *commit* are formalized. Subsequently, the example is reconsidered. Section 6 outlines related work, before the paper is concluded.

2 MOTIVATING EXAMPLE

We introduce as running example a product line of different domain models for *graphs*, a common example in SPL literature (Lopez-Herrejon and Batory, 2001). In this section, we conduct the example using a "traditional" tool chain: A state-of-the-art VCS supports the development of the platform in multiple iterations. Next, a feature model is defined, and an MDPLE tool based on negative variability is used to annotate domain model elements with variability information. During *application engineering*, we derive one example product.

Variability Model. Figure 3 shows the underlying feature model, which consists of a root feature `Graph` with two *mandatory* sub-features `Vertices` and `Edges`. Vertices may optionally be `colored`. For edges, the optional sub-features `weighted` and `labeled` are defined. Furthermore, the features `directed` and `undirected` are mutually exclusive.

Platform. The *superimposition* is defined in the form of a *multi-variant domain model* (*MVDM*) (Gomaa, 2004). We realize the platform in multiple VC iterations, after each of which a *commit* is carried out. In Table 1, the performed modifications are listed. When referring to the feature model in Figure 3, one feature has been realized at a time. Figure 4 shows the resulting MVDM.

Feature Mapping. After having defined the variability model and the platform, they need to be connected. In an MDPLE approach based on negative variability, this requires assigning *feature expressions* to MVDM elements. A mapping for the example

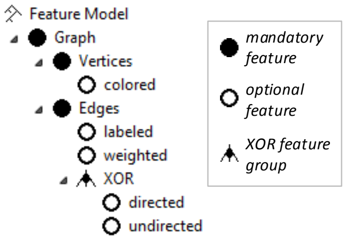


Figure 3: Feature model for the *graph* product line, shown in the tree diagram syntax provided by *SuperMod*.

Table 1: History of the developed multi-variant domain model for the *graph* product line. Within each revision, the inserted elements are listed by their respective qualifier. For all associations, the corresponding member ends have been inserted in the same revision.

	Inserted elements	**Commit message**
1	—	"Initial commit."
2	Class `Graph`	"Realization of root feature Graph."
3	Class `Vertex`, association `has vertices`	"Realization of feature Vertices."
4	Class `Edge`, association `has edges`	"Realization of feature Edges."
5	Property `Edge::label`	"Realization of feature labeled."
6	Property `Edge::weight`	"Realization of feature weighted."
7	Association `connects`	"Realization of feature undirected."
8	Association `starts at` and `ends at`	"Realization of feature directed."
9	Class `Color`, property `Color::name`, association `has color`	"Realization of feature colored."

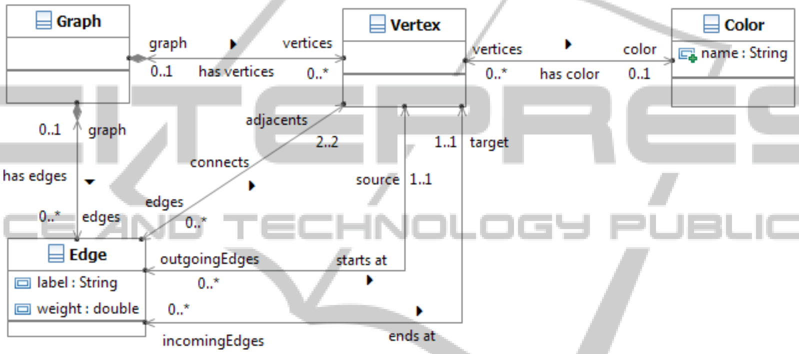
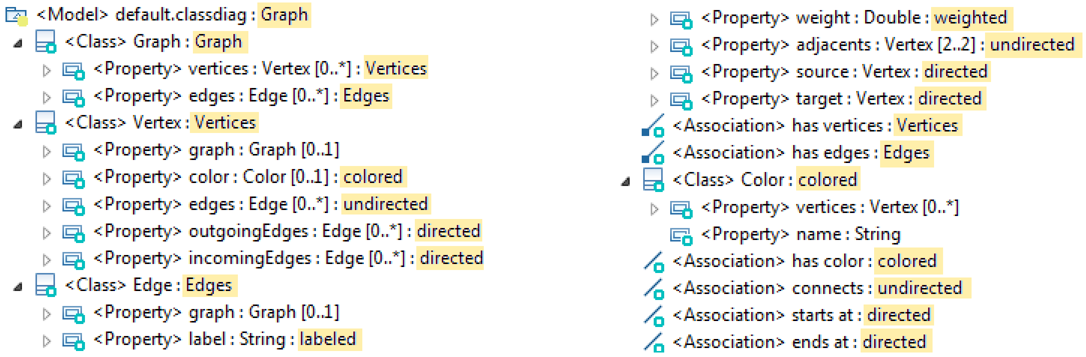


Figure 4: Multi-variant domain model, which realizes all features of the *graph* product line as a superimposed UML class diagram. The diagram has been created using the EMF-based UML modeling tool *Valkyrie* (Buchmann, 2012).



<Model> default.classdiag : Graph
<Class> Graph : Graph
<Property> vertices : Vertex [0..*] : Vertices
<Property> edges : Edge [0..*] : Edges
<Class> Vertex : Vertices
<Property> graph : Graph [0..1]
<Property> color : Color [0..1] : colored
<Property> edges : Edge [0..*] : undirected
<Property> outgoingEdges : Edge [0..*] : directed
<Property> incomingEdges : Edge [0..*] : directed
<Class> Edge : Edges
<Property> graph : Graph [0..1]
<Property> label : String : labeled
<Property> weight : Double : weighted
<Property> adjacents : Vertex [2..2] : undirected
<Property> source : Vertex : directed
<Property> target : Vertex : directed
<Association> has vertices : Vertices
<Association> has edges : Edges
<Class> Color : colored
<Property> vertices : Vertex [0..*]
<Property> name : String
<Association> has color : colored
<Association> connects : undirected
<Association> starts at : directed
<Association> ends at : directed

Figure 5: Mapping between the multi-variant domain model and the feature model, realized by *feature expressions*, logical expressions on the set of feature variables defined in the feature model in Figure 3. The mapping has been realized with the help of the MDPLE tool *FAMILE* (Buchmann and Schwägerl, 2012), where the mapping is defined on the abstract syntax tree of the MVDM. Feature expressions are highlighted.

product line is shown in Figure 5. where a total of 22 feature annotations is necessary.

Application Engineering. To automatically derive specific products from the product line, *feature configurations* are specified which bind each feature to a selection (either *selected* or *deselected*). For instance, the feature configuration from Figure 6 produces the product shown in Figure 7, a directed and weighted graph.

Drawbacks. Although having successfully applied an "off-the-shelf" combination of VC and MDPLE in the initial example, we raise several issues.

- Variability in time and variability in space are managed by means of two *different mechanisms*. Therefore, the user has to repeatedly specify versioning information (i.e., feature expressions) for

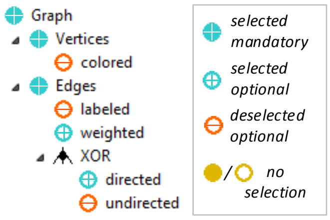


Figure 6: An example feature configuration.

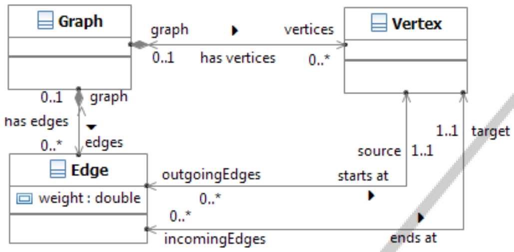


Figure 7: An example product that corresponds to the feature configuration shown in Figure 6.

the same change. All manually provided mapping information (see Figure 5) could have been inferred from commit messages.

- In the case of *product specific adaptations*, the connection to the product line gets lost. When SPL developers find a bug in a product, the question arises, whether it is transferred from the MVDM or due to mistakes in the mapping. In case the MVDM is erroneous, the bug must be fixed twice, in the product and in the platform. There is no mechanism for propagating product changes back into the product line.
- For the development of the multi-version platform, developers are *constrained by single-version rules*. E.g., it is impossible to specify an alternative name `DirectedEdge` for the class `Edge` in case the feature `directed` is selected. This restriction is not imposed on the evolution of the platform: It is possible to change the class name within subsequent revisions.

In Section 4, the tool *SuperMod* is presented, which allows to overcome the presented drawbacks. We will revisit the *graph* example in Section 5.

3 COMPARISON: VC AND SPLE

In this section, we compare terms and notions of VC and SPLE that have been used in the previous two sections. This comparison motivates the prototype SuperMod, which is described in Section 4. Table 2 summarizes the discussion below.

Equivalent Concepts. Both VC and SPLE provide an abstraction for the entirety of product versions. In VC, this is a *repository*, whereas in SPLE, this corresponds to the *platform*. For single product versions, the terms *workspace* and *product (configuration)* are used, respectively. As mentioned in the introduction, in both disciplines, there exist two distinct representations. On the one hand, it is possible to store all variants as a *superimposition*, which corresponds to *symmetric deltas* in VCS and to *negative variability* in SPLE. On the other hand, only a minimal core may be defined, which is then extended. This is realized by *directed deltas* in VC and by *positive variability* in SPLE. In both cases, it is necessary to assign *visibilities* either to program fragments or to transformations. These correspond to *version identifiers* (sets or ranges of revisions), and to *presence conditions*, respectively.

Similar Concepts. In both disciplines, there is an abstraction for the set of available versions. In VC, *revision graphs* describe the commit history. In SPLE, *feature models* organize mandatory and/or optional features of a product line within a tree. The specification of a single *version* is done by selection of a *revision*, or by a *feature configuration*, which in turn describes a product variant. In both disciplines, a *filter* operation is realized. In VCS, it populates the workspace after a revision has been selected for *check-out*. In SPLE, filtering is applied as *product derivation* during application engineering.

Differences. Both disciplines deal with different kinds of *variability*. Version control manages *variability in time*, i.e., the fact that a software project is subject to evolution. SPLE, in contrast, deals with *variability in space*, using variability models to describe commonalities and differences among related variants explicitly. In SPLE, it is intended that several configurations of a software project co-exist. This kind of variability has to be planned in advance by suitable *variation points* in the platform. Most SPLE tools require the platform to be free of context-free or context-sensitive conflicts, e.g., a syntactically correct program that is accepted by the respective compiler, or a valid instance of the metamodel in the case of MDPLE. In VC, there are no restrictions concerning product variability: Neither a superimposition nor directed deltas need to be syntactically meaningful; constraints are merely imposed to single-version products. VC and SPLE also differ in terms of version specification. Typically, a VCS fixes the set of versions available for selection (*extensional versioning*, see (Conradi and Westfechtel, 1998)). In SPLE, versions may be described by a combination of features, allowing to create versions that have not been

Table 2: Differences and commonalities among the terms and notions of VC and SPLE.

	Aspect / Generalization	**Version control**	**SPLE**
Equivalent Concepts	All Product versions	Repository	Platform
	Single Product version	Workspace	Product configuration
	Superimposition	Symmetric deltas	Negative variability
	Transformations	Directed deltas	Positive variability
	Visibilities	Version identifiers	Presence conditions
Similar Concepts	Variability model	Revision graph	Feature model
	Version	Revision	Feature configuration
	Filter	Check-out	Product derivation
Differences	Variability kind	Variability in time	Variability in space
	Variation points	Hidden	Explicit
	Product variability	Unconstrained	Constrained
	Version specification	Extensional	Intensional
	Editing model	Filtered	Unfiltered
	Visibility management	Manual	Automatic
	Version membership	Immutable	Mutable
No Equivalence	Automatic visibility update	Commit	—
	Manual visibility update	—	Edit feature mapping

committed earlier (*intensional versioning*). In VC, *filtered editing* is applied. After a check-out, the developer sees and may modify only elements belonging to the selected revision. As soon as a commit is issued, changes are detected in the local workspace, and written back to the repository, while visibilities are updated *automatically*. In contrast, SPLE typically requires the user to edit a multi-version view (*unfiltered editing*) and to manage visibilities (i.e., presence conditions) *manually*. VCS guarantee the *immutability* of version membership of an element: Once committed, it is not possible to remove an element from a revision. In contrast, it is allowed to modify the visibility of an element arbitrarily in SPLE.

No Equivalence. VCS and SPLE tools both offer operations that are not realized by the opposite. Table 2 lists two of each. The VCS operation *commit* detects differences in the workspace in order to write changes back to the repository automatically. No equivalent operation exists in SPLE tools, which would, e.g., allow to propagate product specific modifications back to the platform. Conversely, in SPLE, it is possible to directly modify the *mapping* between the variability model and the platform, i.e., the visibilities. To the best of our knowledge, there exists no VCS that would allow to retrospectively modify version identifiers (which would, indeed, destroy the property of immutable version membership).

Bottom Line. VC and SPLE share an unexpectedly large amount of similarities, particularly with respect to underlying data structures. Most differences are due to the underlying editing models. As we will explain within the subsequent section, SuperMod eliminates these differences by transferring the filtered VC editing model to SPLE. In the workspace, the distinction between variability in time and variability in space is blurred, offering the user new ways of versioning, such as committing a change against a dedicated feature. In particular, the desirable properties of *unconstrained variability*, *intensional versioning*, *automatic visibility management*, and *immutability of (temporal) version membership* are transferred.

4 THE TOOL SuperMod

This section sketches the model-driven implementation of SuperMod. First, we explain theoretical foundations developed in advance. Thereafter, the architecture is described at a coarse-grained level, before we detail the specification by means of a metamodel. Next, the operations *check-out*, *modify* and *commit* are specified. Last, we discuss current limitations and address future tool improvements. The tool is available for evaluation purposes as an Eclipse plug-in (see installation instructions at the end of this paper).

4.1 Underlying Principles

SuperMod realizes the conceptual framework presented in (Schwägerl et al., 2015), which aims at the integration of MDPLE, SPLE, and VC. The framework in turn is built upon the *uniform version model*

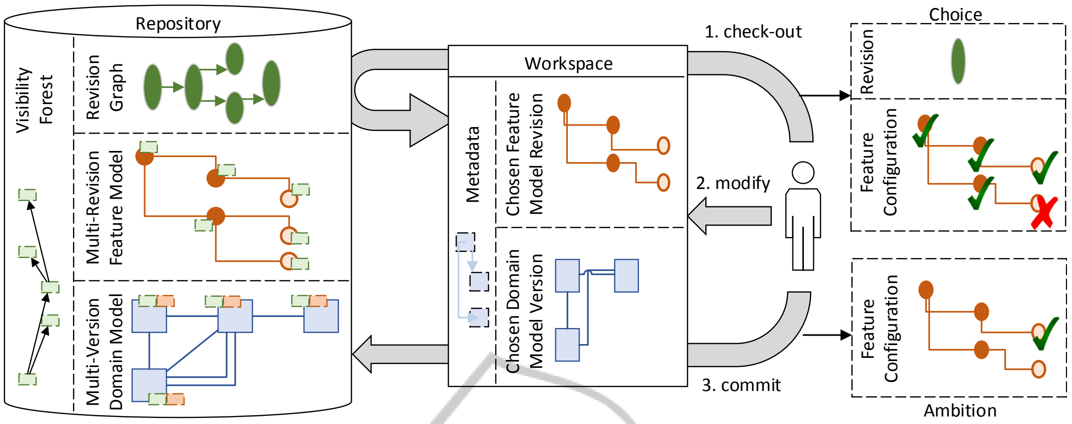


Figure 8: SuperMod tool architecture and editing model.

(Westfechtel et al., 2001), adding higher-level representations for both the version space (by feature models and revision graphs) and the product space (by the use of EMF models). Below, the core concepts of UVM and its extensions are described informally, defining the general notions in Table 2 more precisely.

Options. An *option* is a temporal or logical property of a software system, which may or may not be included in a specific version. In SuperMod, two kinds of options exist: *revision options* and *feature options* (see below).

Choices. A *choice* denotes a single version by assigning a selection (*selected*, *deselected*) to each of the existing options. Choices are used as *read filters*, i.e., they describe versions visible in the workspace.

Ambitions. An *ambition* denotes a set of versions as a subset of all available versions. Ambitions are used as *write filters* in order to delineate the scope of a change performed in the workspace. In contrast to a choice, an ambition may contain *unbound* options, to which the change is immaterial.

Version Rules. The set of available choices and ambitions is constrained by a set of *version rules*, logical expressions over the option set. Version rules are used, e.g., in order to implement constraints such as mutual exclusion within feature models, or to designate subsequent revisions.

Visibilities. A visibility is a logical expression over the option set, which is attached to an element of the feature or domain model. In order to test an element's presence in a specific version, the bindings specified by the respective choice are applied. Visibilities are modified automatically during the commit operation (see below).

4.2 Tool Architecture/ Editing Model

Both the architecture and the editing model of SuperMod are inspired by *distributed VCS* such as Git (Chacon, 2009). The tool offers the traditional version control metaphors *check-out* and *commit* and additionally offers SPLE concepts such as feature models and feature configurations for the definition of the version space and specific versions. The traditional VCS architecture is extended: (1) The feature model is an additional, temporally variable, versioned artifact. (2) The domain model varies along two dimensions, the revision graph and the feature model. Figure 8 illustrates the remarks below.

Repository. A *repository* is a persistent storage linked to a software project under VC. Developers communicate with their private repository by means of the operations *check-out* and *commit*. A SuperMod repository consists of three layers.

- The *revision graph* is a directed acyclic graph that describes the temporal history of a SuperMod project. The graph is extended automatically each time a new revision has been committed. For each revision, a *revision option* is introduced transparently. Furthermore, *version rules* ensure that revision selections amend all predecessor revisions.
- The *multi-version feature model* plays a dual role: Firstly, its evolution is controlled by the revision graph. Secondly, each feature is mapped to a *feature option*, such that the feature model provides an additional version model. Feature model constraints are mapped to *version rules* transparently (Schwägerl et al., 2015).
- The *multi-version domain model* describes the superimposition of the versioned project. Although the term "domain model" is used here, the project may comprise a file hierarchy containing model

or non-model resources. Within the *visibilities* of domain model elements, revision and feature options may occur.

Technically, the repository is an instance of the SuperMod metamodel (see Section 4.3), representing multi-version models (and non-model artifacts) as a superimposition. Thus, from the VC perspective, SuperMod uses symmetric deltas, and from the SPLE perspective, it is based on negative variability.

Visibilities are represented in a memory-optimized way using a global data structure, the *visibility forest*. It contains each visibility occurring on any model element at most once. Furthermore, visibilities may reference each other to form several tree-like structures (hence, a *forest*). The visibility forest is updated during a *commit* transparently.

Workspace. A SuperMod workspace contains the currently selected version of the domain model, i.e., the derived product, in its domain specific representation within an ordinary file system. EMF models are represented as instances of their custom Ecore-based metamodel(s). Plain text and XML files are represented in their custom format. This allows SuperMod users to utilize their single-version editing tools they are familiar with.

During the sub-process *modify*, the user may also edit the feature model arbitrarily, e.g., by introducing new features or constraints. For this purpose, the chosen revision of the feature model is made available for modification in the workspace. Technically, the feature model is represented as an instance of the SuperMod Feature metamodel (Schwägerl et al., 2015).

In addition to the single-version resources, *metadata* are managed transparently to the user. They augment workspace resources with VC details, such as the versioning state (*versioned*, *non-versioned*, *added*, *removed*, etc.). Furthermore, the current *choice* is persisted.

Choices and Ambitions. As mentioned above, *feature configurations* are used to specify choices and ambitions in addition to revision graphs as known from state-of-the-art VCS. A feature configuration is always specified on the current revision of the feature model. When specified as an ambition, the feature configuration may be *partial* and typically binds only few features. The *effective choice/ambition* is formed during check-out/commit as conjunction of the temporal and logical component, e.g., *rev4 and labeled*.

4.3 The SuperMod Metamodel

SuperMod has been developed in a model-driven way using the Eclipse Modeling Framework (Steinberg et al., 2009). Furthermore, the tool has been implemented modularly; it is is not restricted to the three-layer architecture shown in Figure 8, but flexible with respect to the underlying version space space model.

The metamodel realizes the sub-set of concepts presented in Sections 3 and 4.1, which are relevant to the *repository*. As shown in Figure 9, a SuperMod repository consists of a *version space*, a *product space*, and a *visibility forest*. The version space in turn is composed of several *version dimensions*, and the product space comprises a number of *product dimensions*, which in turn contain a hierarchy of *versioned elements*. These may reference a *visibility*, which is organized within a *visibility forest*. A visibility may be an *option reference* or a composed expression (e.g., *and*, *or*, *not*). Choices and ambitions, which occur in SuperMod as temporary data structures (except for the choice in the metadata section), are represented by `OptionBinding`, which maps *options* to *selections*.

On the right hand side of the class diagram, the three dimensions discussed in this paper are depicted. Obviously, the *revision graph* is a subclass of `VersionDimension`. Due to its dual role, the *feature model* is both a *version* and a *product dimension*. The metamodel of the primary product space, the versioned file system, is decomposed into three different resource types: EMF, plain text, and XML. As a representative for `VersionedElement`s, the class `Object` represents multi-version EMF objects. More details on the EMF and Feature multi-version metamodels are provided in (Schwägerl et al., 2015).

4.4 Repository Operations

The user interface of SuperMod has been realized using the *Eclipse Team Provider* API. In this section, we sketch the available UI commands.

Check-Out. For *check-out*, the UI offers two distinct commands: *Switch* prompts the user for a choice in both the revision graph and the feature model, whereas *Update* automatically generates a new choice whose temporal component is updated to the latest available successor of the current revision. In general, the operation check-out has been realized as follows:

- The specified *choice* is recorded in the metadata.
- The feature model is filtered by the temporal component of the selected choice and copied into the local workspace.
- The domain model is filtered by the effective choice and *exported* into the local workspace. The *export* transformation has been implemented for each specific resource type to translate a

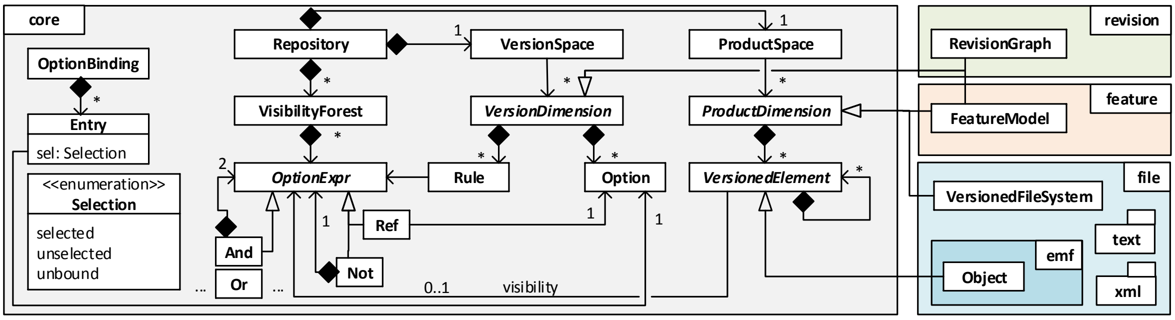


Figure 9: The SuperMod Core metamodel and three extensions as simplified Ecore class diagram.

multi-version representation into its corresponding single-version representation.[1]

Modify. The user may *modify* both the feature model and the domain model within the workspace. For domain model resources, arbitrary editors available in the current Eclipse installation may be used. For the feature model, the command *Edit Version Space* is offered by SuperMod, which opens an EMF tree editor for the current feature model revision. In addition to the modification of versioned resources, the commands *Add/Remove to/from Version Control* are provided, which adjust the corresponding entries within the metadata section accordingly.

Commit. The *Commit* command is defined as a counterpart to the check-out operation as follows.:

- A new *revision* is created as the successor of the revision specified for the choice. Within the given revision of the feature model, the ambition is user-specified as a *partial feature configuration*. For consistency reasons, it is required that the ambition implies the previously specified choice.
- The original state of the workspace version is temporarily restored by applying the recorded choice to the repository. The new state is generated by *importing* (the inverse of *export*) the current workspace into its multi-version representation.
- *Differences* are computed by comparing both versions, the original and the new state.
- Inserted elements are copied into the repository.
- The *visibilities* of inserted/deleted feature model elements are updated automatically by adding/subtracting the temporal component of the ambition to/from the existing visibility.
- The *visibilities* of inserted/deleted domain model elements are updated by adding/subtracting the *effective ambition*.

As proposed in (Schwägerl et al., 2015), the update operations *add* and *subtract* have been implemented by the operators $\vee$ and $\wedge\neg$.

4.5 Current Limitations and Outlook

The current version of SuperMod allows to answer research questions referring to the added value of transferring the VC editing model to SPLE. However, there are some questions that remain to be answered by future work:

- Currently, SuperMod is restricted to *single-user operation* — the repository is persisted locally. After having evaluated and improved the tool, it is planned to realize support for *multi-user operation*. A multi-user version of SuperMod will offer commands similar to the *Push/Pull* operations as defined in the distributed VCS Git (Chacon, 2009). With the number of its users, the size of the repository will grow, concerning both the feature and the domain model. A *transactional storage* will be necessary that scales with large model instances.
- Concurrent modifications will lead to *conflicts* in the domain/feature model, which must be resolved by a specific *three-way merging* component for models, e.g., (Schwägerl et al., 2013).
- The *evolution of the feature model* remains to be further evaluated. For instance, how does the deletion of a feature affect existing variants in the workspace?
- From the SPLE perspective, *domain engineering* and *application engineering* are not clearly separated. SuperMod does not allow to design a multi-variant domain model from scratch and switch to filtered editing in a later phase. Furthermore, derived products are currently considered as volatile

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[1] In the case of EMF models, the export transformation is generic, i.e., there is no necessity to define a custom transformation for each metamodel used.

artifacts in the workspace, which disappear as soon as the choice is changed. It may be desirable to derive several products in a batch mode.

- The concepts of choices and ambitions are hard to grasp for VCS users. Concerning user interaction, there is still room for improvement. For instance, a default ambition might be inferred from the choice and newly introduced features.

5 EXAMPLE REVISITED

To demonstrate the added value of SuperMod, we reconsider the example from Section 2. Now, we develop the platform, consisting of the domain model and the feature model (and the mapping in between, which is hidden now) together in multiple iterations, using feature configurations to describe the scope of changes to the domain model. Figure 10 shows the subsequent iterations in which the model-driven product line is developed as described below. In each step i, revision $i-1$ is evolved to revision i.

Initialization. We create an empty Eclipse project and invoke the *Share* command, which puts it under SuperMod version control. Next, we create an empty UML class diagram and add it to version control. Initially, the feature model is empty. The project is committed to the repository as *revision 1*. Since there is no variability defined in the feature model yet, the user is not prompted for a feature configuration — the change is universal.

Realization of Common Parts. In step 2, both the feature model and the domain model are evolved. We add the root feature `Graph` and its mandatory subfeatures `Vertices` and `Edges` to the feature model. Within the domain model, a class `Graph` is created. Since this class realizes the identically named feature, we specify as ambition a partial feature configuration where `Graph` is selected. Transparently, the visibility of the added features is set to *rev2*, whereas the visibility of the class `Graph` is set to *rev2 and graph*.

Similarly, realizations of the mandatory features `Vertices` and `Edges` are provided in steps 3 and 4, where the feature model remains unmodified. The performed commit operations result in the visibilities *rev3 and vertices* for the class `Vertex` and the association `has vertices`, and *rev4 and edges* for `Edge` and `has edges`.

Realization of Optional Parts. In steps 5 and 6, the optional features `labeled` and `weighted` are introduced. In addition, their realization is provided by performing the following changes in the local workspace: the feature `labeled` is realized as an attribute `label`, and the feature `weighted` as `weight`, both located in the class `Edge`. The change performed in step 6 would also have been applicable in a feature configuration where `labeled` is selected, since the features `weighted` and `labeled` are mutually independent.

Within two subsequent steps, we commit alternative realizations for edges, being `directed` and `undirected`. In step 7, a corresponding XOR-group is introduced to the feature model. In the domain model, a realization for directed edges is added: two associations `starts at` and `ends at` with multiplicity 1 at the `Vertex` end. The realization for undirected edges is committed in step 8 under the ambition *undirected*: an unspecific association `connects` with multiplicity 2 at the `Vertex` end. Since the features `directed` and `undirected` are mutually exclusive, it is ensured that no version containing both realizations may be derived.

In step 9, the optional feature `colored` is introduced and realized by a class `Color` and an association `has color` between `Vertex` and `Color`.

Re-Combination of Independent Features. In the original version of our example, we have derived an example product by specifying the feature configuration shown in Figure 6 in the *application engineering* phase. Since the operations *check-out* and *product derivation* are similar (see Table 2), this step may be "simulated" by checking out a choice that consists of the latest revision and the same feature configuration. As a consequence, the workspace is populated with the domain model version shown in Figure 7. This version may be refined with product specific adaptations (by specifying an ambition that equals the choice) or by changes that influence related products (by specifying as ambition a partial feature configuration that delineates the set of logical versions where the change shall be visible).

Inspecting the Repository. During the described *check-out/modify/commit* iterations, the management of visibilities has been completely automated by the mechanisms described in Section 4.4. As a consequence, a SuperMod user never has to inspect or modify visibilities manually, as it had been necessary in the initial example. Nevertheless, it is interesting to inspect the superimposition and the visibilities defined in the repository for a comparison with the manually defined mapping. Figure 11 depicts the internal state of the repository after step 9. Visibilities of

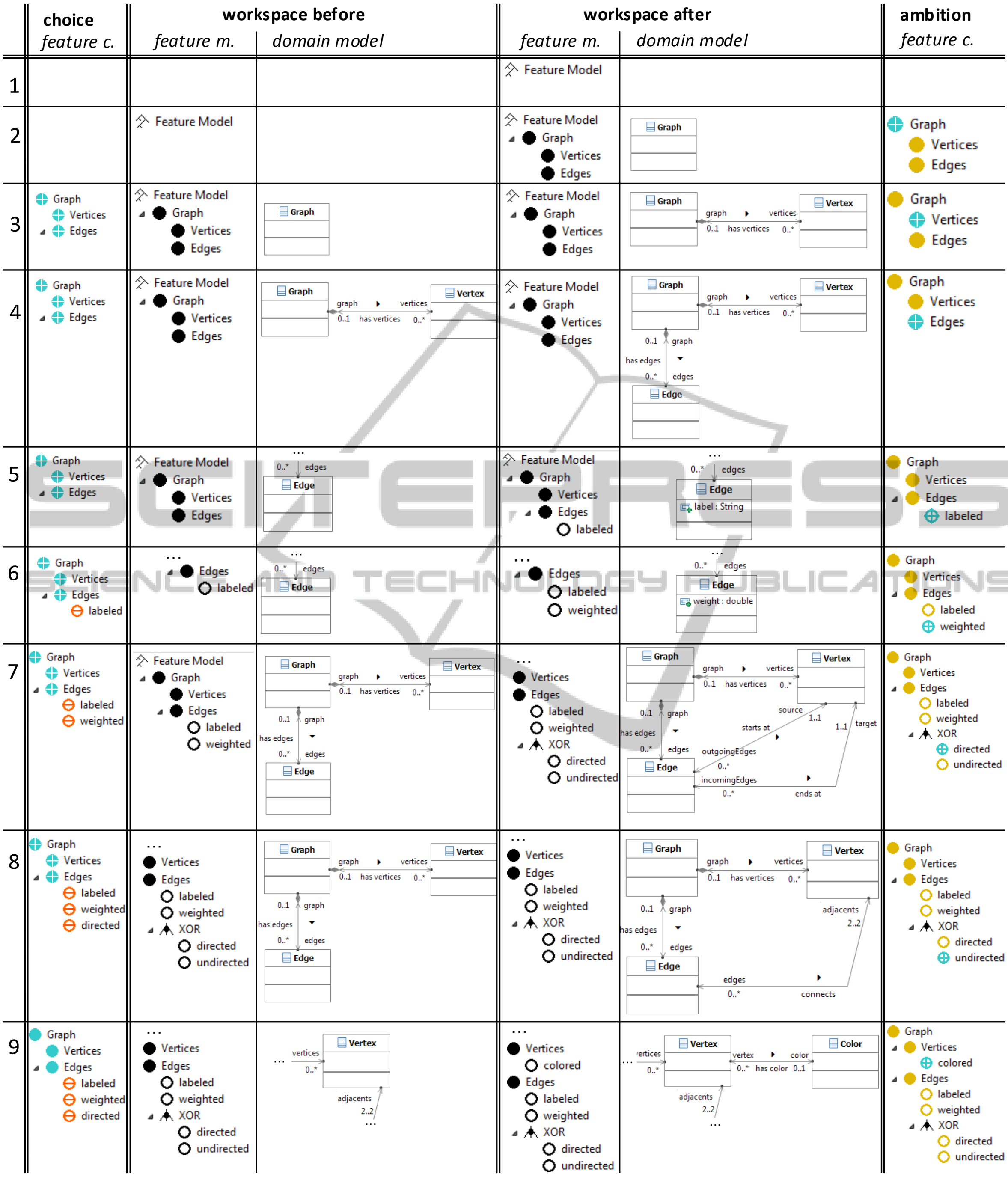

Figure 10: Summary of all performed *check-out/modify/commit* iterations during the example. For the reason of compactness, certain parts of the feature model and domain model have been elided (. . .). For the development of the domain model, *Valkyrie* (Buchmann, 2012) has been used again. All feature models and feature configurations are represented in the tree representation provided by *SuperMod*.

the multi-version feature model only contain revision options, since the feature model is only versioned by the revision graph and not by itself. Visibilities of the MVDM are *hybrid*: they contain a revision part (which corresponds to the version history shown in Table 1) and a feature part (which is equivalent to the mapping shown in Figure 5).

Outlook. The presented example has only scratched the surface of SuperMod. Performed

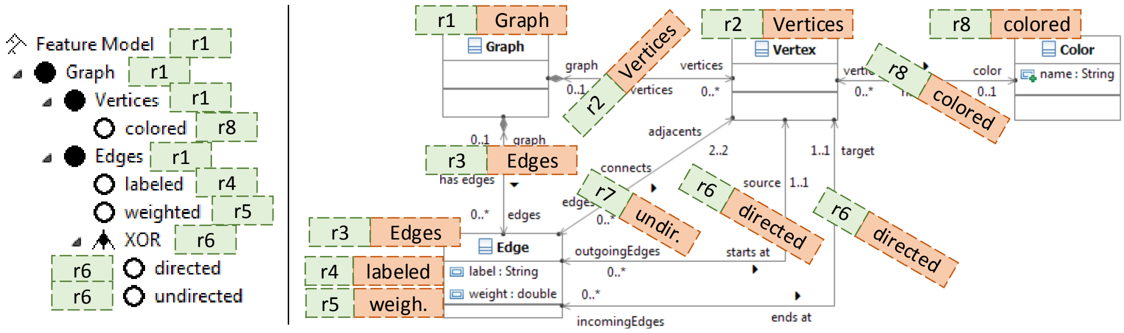

Figure 11: Internal representation of the repository, consisting of the multi-version representations of feature model and domain model, in its state after the example has been conducted. Visibilities of elements are attached using dashed boxes.

modifications were restricted to element insertions, and the specified ambitions always include one selected feature. These simplifications have been applied for the reason of comprehensibility. We informally sketch a couple of extensions to the example, where SuperMod is used in a more advanced way:

- We may add different constructors for the class `Edge`, depending on the combination of features `labeled` and `weighted`. As shown in Figure 12, the features selected in the ambition match the corresponding parameters in different versions of the constructor.
- *Hyper graphs* are a generalization of graphs whose edges connect a number of vertices greater than two. For this purpose, we may add a feature *hyper* below `Edge`. The realization would consist in renaming of the class `Edge` to `HyperEdge` and changing the association name and multiplicities as shown in Figure 13. The co-existence of different class names is only allowed due to SuperMod's property of *unconstrained variability*.
- A universal change may be *retrospectively mapped* to a new feature by reverting the change (i.e., by deleting all added elements and vice versa) and specifying the *negation* of the new feature in the ambition. An example is provided in (Schwägerl et al., 2015, Section 5).
- Our example has been restricted to a single class diagram. SuperMod can handle complete Eclipse projects, including interconnected EMF model resources, and non-model resources such as plain text or XML files. For instance, we may add generated Java code to version control, which would enable for variability in behavioral aspects.

Added Value. When compared to the first version of the example, the *cognitive complexity* of feature mapping has been significantly reduced. The domain model and the feature model have been developed step by step, while realizations for each feature have been specified directly in the workspace. This is enabled by the *uniform version mechanism* for temporal and logical variability in SuperMod, which removes the necessity of *repeated annotations*. For realizing changes, the developer has used an *arbitrary single-version* editor. This is in contrast to many SPLE tools, which require custom multi-variant editors or additional composition languages, which both disrupt the developers' workflow. The additional advantage of *unconstrained variability* has been demonstrated above. In sum, SuperMod removes the drawbacks and limitations that have been identified for an "off-the-shelf" approach to combined VC/SPLE in Section 2.

6 RELATED WORK

In (Schwägerl et al., 2015), concepts and theory used for the realization of SuperMod have been described, including a comparison with the integrating disciplines *Model-Driven Product Line Engineering* (*MDPLE*), *Model Version Control*, and *Software Product Line Evolution*. The current paper describes the added value from the end user's perspective. Subsequently, we compare SuperMod to other tools and approaches that partially share VC and SPLE concepts.

With *branches*, many contemporary version control systems, e.g., Git (Chacon, 2009) and Subversion (Collins-Sussman et al., 2004) offer logical variants to a limited extent. However, the current state of the art only allows to restore variants that have been committed earlier (*extensional* versioning), but not to recombine new variants based on predicates similar to feature configurations (*intensional* versioning).

In (Reichenberger, 1995), an approach for *orthogonal* version management is proposed. A version cube is formed by product, revision, and variant space. Albeit, this approach does not consider the variant space to be subject to temporal evolution.

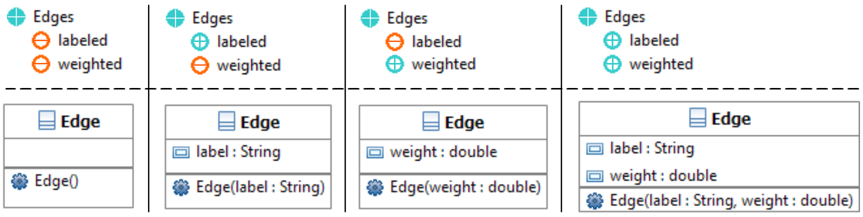

Figure 12: Four additional changes, which add different constructors to the class `Edge`, each with a corresponding ambition.

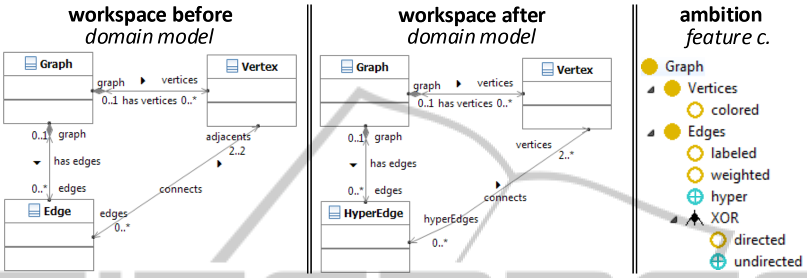

Figure 13: Additional change realizing the feature *hyper*, associated with a corresponding ambition.

The tool SuperMod presented in this paper builds upon the *uniform version model* (UVM) presented in (Westfechtel et al., 2001). UVM's basic concepts (*options*, *visibilities*, *constraints*) have been initially introduced in the context of *change-oriented versioning* (*CoV*) (Munch, 1993). The tool *EPOS-DB* is an implementation of CoV concepts. In contrast to SuperMod, both the version space and the product space are represented at a low level of abstraction (propositional formula and text files, respectively).

In (Zeller and Snelting, 1997), an approach to *unified versioning* based on *feature logic* is presented. Versions of text files are stored with selective deltas; visibilities are controlled by feature-logical expressions. Constraints on feature combinations are expressed by (low level) version rules.

In (Walkingshaw and Ostermann, 2014), an approach to filtered (*projectional*) editing of multi-variant programs is described. Like in our work, the motivation is a reduction of complexity gained by hiding variants not important for a specific change to a multi-variant model. Visibilities are managed automatically, but in contrast to our approach, the *choice* always equals the *ambition*. Furthermore, the restriction of a *completely bound choice* does not exist since the user operates on a partially filtered product which still contains variability. Our tool presented in this paper ensures a relaxed form of the *edit isolation principle* discussed in (Walkingshaw and Ostermann, 2014, Section 4): a change may affect only those variants that are included in the specified ambition.

Using *Stepwise and Incremental Software Development* (Apel and Kästner, 2009), a sub-discipline of *Feature-Oriented Software Development*, features are described as *refinements* or *layers*. This replaces the necessity of an explicit mapping in the form of presence conditions, but the increments need to be specified in a form that deviates from the "normal" implementation language, e.g., model transformations. In contrast, SuperMod enables for SISD using a familiar development environment.

The source-code centric tool *CIDE* (*Colored IDE*) (Kästner et al., 2008) generalizes preprocessors using a colored representation to distinguish features. CIDE is based on negative variability and offers the possibility to temporarily restrict a variational project to *views* on a specific feature or variant. Then, irrelevant source code fragments are hidden. The performed changes only affect the selected feature or variant, i.e., *choice* and *ambition* must be equal.

The MDPLE tool *Feature Mapper* (Heidenreich et al., 2008), which is based on negative variability, offers the possibility of *change recording* during domain engineering. Having selected one or several features and invoked the *record* operation, all changes performed are associated with a feature expression derived from the provided feature selection. However, only *insertions* are supported, and change recording is restricted to GMF-based editors.

7 CONCLUSION

In this paper, we have presented *SuperMod*, a model-driven tool that combines the management of variability in time and variability in space, i.e., version control (VC) and Software Product Line Engineering (SPLE). Typical SPLE processes distinguish between *domain engineering*, where a platform and a variability model are defined, and *application engineering*, where variability is resolved to automatically derive specific products. In contrast, in VC, software is developed iteratively. SuperMod bridges this gap by transferring VC metaphors to SPLE. For the selection of versions during check-out and commit, *feature configurations* are specified in addition to a selection among the revision graph. The mapping between the platform and the variability model is managed automatically.

In a running example, where a product line of *graph* domain models has been developed, we have demonstrated many advantages of the VC/SPLE integration. Due to the filtered editing model, the versioning overhead is notably small when compared to existing SPLE approaches. For workspace modifications, the developer is not restricted by single-version constraints. Furthermore, a familiar development environment can be used. *Intensional* version specification allows for the definition of feature configurations as version descriptions. These advantages are boosted by using models as higher-level descriptions of the versioned software system.

Future work will address the development of a multi-user component, which will advance SuperMod to a full-fledged distributed VCS. The evolution of the feature model will be subject to research. Furthermore, a detailed evaluation against SPLE tools will be conducted, using a real-world example. The obtained results will be important to understand the impact of the filtered SPL editing model on the underlying development processes and tool chains.

TOOL AVAILABILITY

The research prototype *SuperMod* is available as a set of Eclipse plug-ins under the Eclipse Public License. The plug-ins may be installed into a clean Eclipse Luna Modeling distribution using the following update site (*Help — Install new Software*):

```
http://btn1x4.inf.uni-bayreuth.de/
                        supermod/update
```

In order to reproduce the example provided in this paper, at least the items *SuperMod Core* and *SuperMod Revision+Feature Layered Version Model* should be selected for installation.

After having installed the plug-ins, SuperMod version control may be added to arbitrary Eclipse projects using the operation *Team — Share Project* and selecting the `SuperMod` repository connector. After that, the operations *Team — Commit* and *Team — Update/Switch* are available in order to communicate with the locally persisted repository. The feature model may be edited by *Team — Edit Version Space*.

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