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Tracing Imperfectly Modular Variability in Software Product Line Implementation

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Abstract. When large software product lines are engineered, a combined set of traditional techniques, *e.g.*, inheritance, design patterns, generic types, is likely to be used for realizing the variability at the implementation level. In these techniques the concept of feature, as a reusable unit, does not have a first-class representation in implementation, but still an imperfect form of modularization of variability can be achieved. We present in this paper a framework (*i*) to explicitly capture and document this imperfectly modular variability – by several combined techniques – in a dedicated variability model, and (*ii*) to establish trace links between this model and the variability model at the specification level. We report on the implementation of the framework through a domain specific language, and show the feasibility of the approach on a real feature-rich system.

1 Introduction

In *Software Product Line Engineering* (SPLE), the core software assets are developed during the domain engineering phase [13] and represent those reusable artifacts and resources that form the basis for eliciting the single software products during the application engineering phase. Core assets are made reusable by modeling and realizing what is common and what is going to vary, *i.e.*, the commonality and the variability, between the related products in a methodological way. In realistic SPLs, where variability is extensive, a crucial issue is the ability to manage it in these different core assets among different abstraction levels [5]. An important aspect of the variability management activity is then the ability to trace a variable unit, commonly known as a *feature* [10], along the SPLE phases.

Traceability is defined as the ability to describe and follow the life of a software artifact forward and backward along the software lifecycle [2, 7]. In SPLE there are four main dimensions of traceability: refinement, similarity, variability, and versioning traceability [2, 13]. Variability traceability "*is dealt by capturing variability information explicitly and modeling the dependencies and relationships separate from other development artifacts*" [4]. In this work we focus on an analysis of the variability traceability between the specification and implementation level, *i.e.*, on the *realization* trace links [2, 13] to the core-code assets.

The results of a recent survey on SPLE traceability, by Kim et al. [12], show that none of the current approaches fully support end-to-end traceability,

and there are unexplored research areas in these approaches. To the best of our knowledge, no variability traceability and management approach at the implementation level, *e.g.*, [3,4,6,9,13,14], is currently addressing the early steps of capturing and modeling the variability when a subset of traditional techniques (*e.g.*, inheritance, design patterns, generic types) are used in combination, as in many realistic SPL settings [3,8,9].

In this paper, we propose an approach for tracing variability between the specification level and, what we name *imperfectly modular variability*¹ at the implementation level. We distinguish both levels in a way similar to Becker [3]. Our contribution is a tooling framework (Sec. 3) that gives support from the early steps of variability traceability, *i.e.*, from the capturing and modeling of the variability in core-code assets. Unlike other works that tackled similar issues [6,9,14] we show how to capture and model the variability when it is implemented by several traditional techniques in combination. We keep the variability information separated from the core code assets as by Berger et al. [4] and Pohl et al. [13]. Further, as the variability to be represented may be large [13], our framework fosters the documentation of the implemented variability in a fragmented and flexible way, inspired by Kästner et al. [11]. We also report on our implementation of the framework by a *Domain Specific Language* (DSL), and on its application to a feature-rich system, showing its feasibility (Section 4).

2 Motivations

Background. We consider that the variability of an SPL is documented in a Variability Model (VM), which is commonly expressed as a Feature Model (FM) [10]. An FM is mainly used at the specification level for scoping the software products within an SPL in terms of *features*. On the other hand variation points (*vp*-s) are places in a design or implementation that identify locations at which the variation occurs [9], and the way that a *vp* is going to vary is expressed by its *variants*.

Variability traceability can be established and used for different reasons, and by different stakeholders [2,7]. It is mainly used for (semi)automating different processes in SPLE, *e.g.*, for resolving the variability (product derivation), evolving, checking consistency, addressing, or comprehending the variability.

Imperfectly Modular Variability. For illustration and validation we use *JavaGeom*², an open source geometry library for Java that is architected around well identified features. Although not presented as an SPL, JavaGeom is a relevant and easily understandable case for demonstrating the applicability of our framework on the equivalent of a medium-size SPL. Let us consider the implementation of a set of features as depicted in the FM on Fig. 1. `StraightCurve2D` is a mandatory feature with three shown alternative features: `Line2D`, `Segment2D`, and `Ray2D`. Focusing on the realization techniques (*cf.* Fig. 2), the abstract class

¹ This notion is defined in Sec. 2 using a real feature-rich system.

² <http://geom-java.sourceforge.net/index.html>

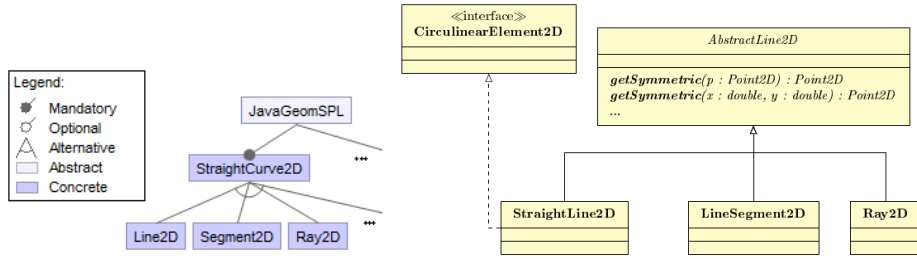


Fig. 1: Features from *JavaGeom* Fig. 2: A detailed design excerpt of *JavaGeom*

`AbstractLine2D` is a *vp* and its three variants, *i.e.*, `StraightLine2D`, `LineSegment2D`, and `Ray2D`, are created by generalizing/specializing its implementation. Features from Fig. 1 seem to have a direct and perfect modular mapping in implementation (*cf.* Fig. 2), *e.g.*, «`StraightCurve2D` implemented by `AbstractLine2D`», or «`Line2D` implemented by `StraightLine2D`». But actually, this perfect modularity hardly exists.

Imperfect modularity comes from the fact that a feature is a domain concept and its refinement in core-code assets is a *set* of *vp*-s and *variants* (even if they are modular), *i.e.*, it does not have a direct and single mapping. For example, the feature `Line2D` uses several *vp*-s, such as `AbstractLine2D` and `CircilinearElement2D` (other *vp*-s are not shown), the variant `StraightLine2D` (*cf.* Fig. 2), plus their technical *vp*-s (Sec. 3.2), as the `getSymmetric()` *vp* of the `AbstractLine2D`. When a combined set of traditional techniques are used for implementing the variability, *e.g.*, inheritance for `StraightCurve2D`, overloading for `getSymmetric()`, the code is not shaped in terms of features. Therefore, the trace relation is *n-to-m* between the specified features to the *vp*-s and *variants* at the implementation. Moreover an SPL architect has to deal with a variety of *vp*-s and *variants*.

Our approach addresses the ability to trace this imperfectly modular variability in implementation, which we define as follows: *An imperfectly modular variability in implementation occurs when some variability is implemented in a methodological way, with several implementation techniques used in combination, the code being not necessarily shaped in terms of features, but still structured with the variability traceability in mind.*

3 A Three Step Traceability Approach

To trace imperfectly modular variability in implementation, we propose an approach that follows three main steps (*cf.* Fig. 3): ① capturing the implemented variability in terms of *vp*-s and *variants*, as abstract concepts, ② modeling (documenting) the variability in terms of *vp*-s and *variants*, while keeping the consistency with their implementation in core-code assets, and ③ establishing the trace links between the specified and implemented variabilities.

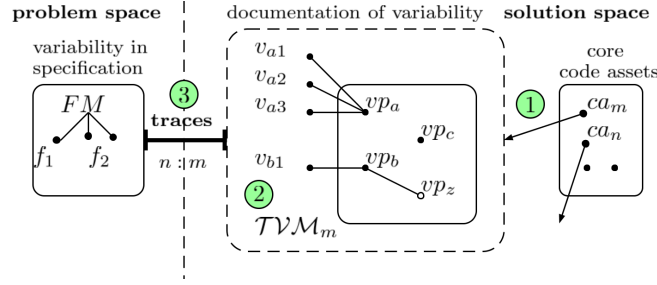


Fig. 3: Proposed traceability approach (\mathcal{TVM}_m stands for *Technical Variability Model* (cf. Sec. 3.2) of the core-code asset ca_m , with vp -s $\{vp_a, vp_b, \dots\}$ and their respective variants $\{v_{a1}, v_{a2}, \dots\}$. While, $\{f_1, f_2, \dots\}$ are features in the FM.)

3.1 Capturing the Variability of Core-Code Assets (Step ①)

The core-code assets that realize variability usually consist of a common part and a variable part. It can happen that a whole asset is also a variable asset. A core-code asset can be, *e.g.*, a source file, package, class. The variable part consists of a mechanism (*i.e.*, technique) for creating the variants, a way for resolving the variants, and the variants themselves. They are abstracted using the concepts of *variation points (vp-s)*, *variants*, and their dependencies.

Let the set of all vp -s in an SPL be $\mathcal{VP} = \{vp_a, vp_b, vp_c, \dots\}$ for the set of core-code assets, with variability or variable, $\mathcal{CA} = \{ca_m, ca_n, ca_o, \dots\}$. We assume that a $vp_x \in \mathcal{VP}$ is implemented by a single traditional technique $t_x \in \mathcal{T}$. The set \mathcal{T} of possible techniques for vp_x is then made explicit in our framework,

$\mathcal{T} = \{\text{Inheritance, Generic Type, Overriding, Strategy pattern, Template pattern, \dots}\}$

A vp is not a by-product of an implementation technique [5], therefore we have to tag it in some way. "Tagging a vp " means to map the $vp_x \in \mathcal{VP}$ concept to its concrete varying element of any $ca_x \in \mathcal{CA}$. For example, we abstract/tag the superclass `AbstractLine2D` (cf. Fig. 2) with `vp_AbsLine2D`, and its subclasses as variants `v_Line2D`, `v_Segment2D`, and `v_Ray2D`, respectively. Depending on the size of variability and the used technique, the nature of a core asset element that represents a vp varies. We gathered their variety as *characteristic properties of vp-s*. Their properties that are important to be captured are: granularity, relation logic, binding time, evolution, and resolution.

Granularity. A vp in a core-code asset can represent a coarse-grained element that is going to vary, *e.g.*, a file, package, class, interface; a medium-grained element *e.g.*, a method, a field inside a class; or a fine-grained element *e.g.*, an expression, statement, or block of code.

Logic Relation (LG). The set of the logic relations between variants in a vp , that are commonly faced in practice, is similar to the possible relations between features in an FM. Thus, a $t_x \in \mathcal{T}$ offers at least one of these logic relations,

$\mathcal{LG} = \{\text{Mandatory, Optional, Alternative, Multi-Coexisting}\}$

Binding Time (BT). Each vp is associated with a binding time, *i.e.*, the time when is decided for its variants, or when they are resolved. Based on the available taxonomies [6], the possible binding times for the vp_x are:

$BT = \{\text{Compilation, Assembly, Programming time, Configuration, Deploy, StartUp, Runtime}\}$

Evolution (EV). Depending on whether a vp is meant to be evolved in the future with new variants or not, it can be $EV = \{\text{Open, Close}\}$.

For example, the `vp_AbsLine2D` has a class level granularity (*cf.* Fig. 2). It is resolved at runtime to one of its alternative variants, `v_Line2D`, `v_Segment2D`, or `v_Ray2D`, and we tag it as open as it is implemented as an abstract class.

Another characteristic property of a vp is how it is resolved, *i.e.*, whether a variant is added, removed or replaced by another variant. This matters during the process of product derivation, which is a possible usage of our framework.

3.2 Modeling the Implemented Variability (Step ②)

During this phase, the variability of a core-code asset ca_x is modeled in terms of vp -s and *variants* as abstractions (*cf.* Fig. 3, step ②). We distinguish five types of vp -s that can be chosen from:

$\mathcal{X} = \{\text{vp, vp_unimpl., vp_technical, vp_optional, vp_nested}\}$

A resolution for each of them is given in Tbl. 1. The implementation technique $t_x \in \mathcal{T}$ of the $vp_x \in \mathcal{VP}$, which relation we write as (vp_x, t_x) , describes three main properties of the vp_x : the relation logic for its variants, the evolution, and the binding time. Possibly, other properties can also be abstracted and attached. Then, $t_x = \{lg_x, ev_x, bt_x, \dots\}$, where $lg_x \in \mathcal{LG}$, $ev_x \in \mathcal{EV}$, and $bt_x \in \mathcal{BT}$. So, when the vp_x is an ordinary vp (*cf.* Tbl. 1) we model the variability in a core-code asset as a set of its *variants* $\mathcal{V} = \{v_{x1}, v_{x2}, v_{x3}, \dots\}$, and the characteristic properties derived from the vp_x 's implementation technique t_x . This leads to the following definition:

$$vp_x = \{\mathcal{V}, t_x\} = \{\{v_{x1}, v_{x2}, v_{x3}, \dots\}, t_x\} \quad (1)$$

As an illustration we present the ordinary vp_x (*cf.* Tbl. 1) as in Fig. 4, numbered with 1. Similarly, a technical vp , *e.g.*, the technical vp_a of vp_y , is represented as in 2. An optional vp is modeled as the vp_z in 3. We use the acronym *opt* here in order to distinguish between the optional relations between variants in a vp and the optionality of the vp itself. Moreover a nested vp is illustrated as the nested vp_b of vp_z , where the variant v_{z2} of vp_z represents a common part for its three variants $\{v_{b1}, v_{b2}, v_{b3}\}$. Finally, the $vp_c = \{\{\emptyset\}, t_c\}$ in 4 is an unimplemented vp . These types of vp -s can be combined, *e.g.*, an optional vp can be ordinary, unimplemented, or can have other nested or technical vp -s.

Instead of modeling the whole implemented variability at once and in one place, we model it in a fragmented way. A fragment can be any unit (*i.e.*, a package, a file, or a class) that has its inner variability and that is worth to be separately modeled. For this reason, we designed specific models, named as

Table 1: Types of variation points that are commonly faced in practice

Types	Description
Ordinary	<i>A vp is introduced and implemented (i.e., its variants are realized) by a specific technique.</i>
Unimplemented	<i>A vp is introduced but is without predefined variants (i.e., its variants are unknown during the domain engineering).</i>
Technical	<i>A vp is introduced and implemented only for supporting internally the implementation of another vp, which realizes some of the variability at the specification level.</i>
Optional	<i>The vp itself, not its variants, is optional (i.e., when it is included or excluded in a product, so are its variants).</i>
Nested vp	<i>When some variable part in a core-code asset becomes the common part for some other variants.</i>

Technical Variability Models (\mathcal{TVM}), which are created and maintained locally, *i.e.*, closer to the core-code assets (*cf.* Fig. 3). They contain the abstractions of *vp*-s and *variants*, their tags with core asset elements, and describe the variability of a specific core-code asset. For example, the variability of a ca_m with six different *vp*-s is modeled by the \mathcal{TVM}_m as in Fig. 4.

All the \mathcal{TVM} s together constitute the *Main Technical Variability Model* (\mathcal{MTVM}). Unlike the organization of features in an FM as a tree structure, in \mathcal{MTVM} the *vp*-s reside in a forest-like structure. Moreover, the meaning of a *vp* is extended, *i.e.*, it is the place at which the variation occurs [9], and represents the used technique to realize the variability.

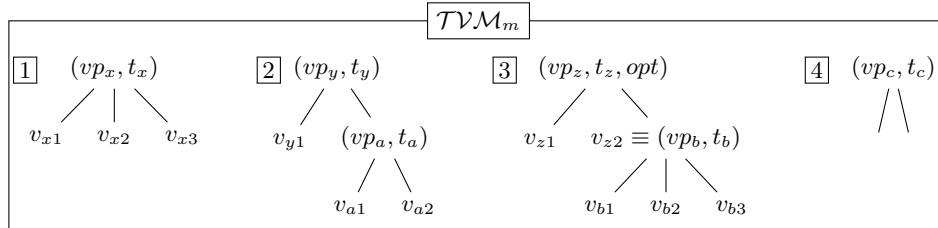


Fig. 4: An example of the Technical Variability Model (\mathcal{TVM}_m) for a ca_m

3.3 Establishing the Trace Links (Step ③)

The last step of our approach (*cf.* Fig. 3, step ③) is to map the variability between the VM at specification level (*i.e.*, features in an FM) and the \mathcal{MTVM} at implementation level (*i.e.*, *vp*-s and *variants*), by establishing the trace links between them.

Let us suppose that $f_x \in \mathcal{FM}$ is a variable feature at specification level, where $\mathcal{FM} = \{f_1, f_2, f_3, \dots\}$. For mapping features to *vp*-s, we use a single bidirectional type of trace links **implementedBy** (\mapsto) or **implements** (\longleftarrow), which

presents the *variability realization* trace link in implementation. When f_x is implemented ideally by a single variation point vp_x , or conversely, we write: $f_x \mapsto vp_x$, or `implementedBy(f_x, vp_x)`. Similarly, f_x can be implemented by a single variant $v_{xn} \in \mathcal{V}$ (cf. Sec. 3.2), *i.e.*, $f_x \mapsto v_{xn}$. For example, the feature `StraightCurve2D` (cf. Fig. 1) is implemented by `vp_AbsLine2D` (cf. Fig. 2), *i.e.*, `StraightCurve2D` \mapsto `vp_AbsLine2D`, or `Ray2D` \mapsto `v_Ray2D`. When f_x is implemented by several vp -s, which can be from the same core-code asset or not, then $f_x \mapsto \{vp_x, vp_y, vp_z, \dots\}$.

The mapping between features and vp -s is a partial mapping, as some features in \mathcal{FM} are abstract features (*i.e.*, do not require an implementation), or they can be deferred to be implemented later.

4 Implementation and Application

We implemented the proposed framework as an internal DSL in Scala. The interoperability between Java and Scala enabled us to use the DSL in JavaGeom. To document and trace variability, the DSL provides two modules `fragment` and `traces`, respectively. We used them to analyse 92% of the 35,456 lines of code from JavaGeom. The successful documentation phase resulted in 11 \mathcal{TVM}_s , all of them being at the package level. We observed that vp -s in JavaGeom are implemented using up to three techniques, inheritance, overloading, and generic types. Then, we established the trace links between the specified features (cf. Fig. 1, which consist of 110 features extracted from its documentation) to the vp -s and *variants* in implementation (cf. Fig. 2). We successfully traced 199 vp -s, with 269 *variants*, showing the feasibility of our approach.

Capturing and documenting different types of vp -s and their implementation techniques during the variability traceability, as in JavaGeom, becomes important during the usage of trace links. For example, the relation logic between the variants in a vp is needed to check the consistency between the variability at the specification and implementation level. Similarly, knowledge of the binding time of vp -s is necessary during the product derivation.

5 Conclusion

Tracing the variability between the specification and implementation levels is an important part of the development process in SPL engineering. At the implementation level, a combination of traditional variability implementation techniques are actually used in many realistic SPLs, thus leading to a form of *imperfectly modular variability* in implementation. The key contribution of our approach is a three-step framework for capturing, documenting, and tracing this imperfectly modular variability, together with some DSL-based tool support.

A limitation of the DSL, but not of the framework itself, is that we could not apply it for tracing the variability at the finest granularity level, *e.g.*, at the expression level, as our internal DSL in Scala uses reflection for tagging the variability. Although using reflection is not mandatory, this helps to keep the strong

consistency between the abstractions of *vp-s* and *variants* with the core-code assets themselves. Although we used the DSL successfully in a real feature-rich system, we plan to extend this framework in supporting the documentation of the dependencies between the *vp-s* themselves and to integrate the DSL with another DSL that models the variability specifically at the specification level, such as FAMILIAR [1]. With these two extensions, we plan to apply our variability traceability framework to (semi)automated consistency checking of variability between the specification and implementation levels on several case studies.

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