



# Variability Modules for Java-like Languages

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## ABSTRACT

A Software Product Line (SPL) is a family of similar programs (called variants) generated from a common artifact base. A Multi SPL (MPL) is a set of interdependent SPLs (i.e., such that an SPL's variant can depend on variants from other SPLs). MPLs are challenging to model and implement efficiently, especially when different variants of the same SPL must coexist and interoperate. We address this challenge by introducing variability modules (VMs), a new language construct. A VM represents both a module and an SPL of standard (variability-free), possibly interdependent modules. Generating a variant of a VM triggers the generation of all variants required to fulfill its dependencies. Then, a set of interdependent VMs represents an MPL that can be compiled into a set of standard modules. We illustrate VMs by an example from an industrial modeling scenario, formalize them in a core calculus, provide an implementation for the Java-like modeling language ABS, and evaluate VMs by case studies.

## CCS CONCEPTS

• **Software and its engineering** → **Software product lines; Modules / packages; Classes and objects.**

## KEYWORDS

ABS language, Delta-oriented programming, Language design, Modules, Multi product line, Variant generation

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## 1 INTRODUCTION

Modeling variability aspects of complex software systems poses challenges currently not adequately met by standard approaches to software product line engineering (SPL) [7, 30]. A first modeling challenge is the situation when more than one product line is involved and these product lines depend on each other. Such sets of related and interdependent product lines are known as a multi product line (MPL) [18, 44]. A second modeling challenge, orthogonal to MPLs, is the situation when different product variants from the same product line need to co-exist in the same context and must be interoperable [10].

In Sect. 2 we exemplify these two challenges in the context of an industrial case study from the literature [22, 24], performed for Deutsche Bahn Netz AG, where: (i) several interdependent product lines for networks, signals, switches, etc., occur; and (ii) for example, mechanic and electric rail switches are different variants of the same product line, and some train stations include both. Overall, MPLs give rise to the quest for mechanisms for hiding implementation details, reducing dependencies, controlling access to elements, etc. [18].

We take the standard concept of a module [45], used to structure large software systems since the 1970s, as a baseline. Software modules are supported in many programming and modeling languages, including ABS, Ada, Haskell, Java, Scala, to name just a few. Because modules are intended to facilitate interoperability and encapsulation, no further *ad hoc* concepts are needed for this purpose. We merely *add variability* to modules, rendering each module a product line of standard, variability-free modules. We call the resulting language concept *variability module* (VM).

The main advantage of VMs is their conceptual simplicity: as a straightforward extension of standard software modules, they are intuitive to use for anyone familiar with modules and with software product lines. Each VM is both a module and a product line of modules. This reduction of concepts not only drastically simplifies syntax, but reduces the cognitive burden on the modeler. We substantiate this claim: in Sect. 2 we illustrate the railways MPL case study in terms of VMs without the need to introduce any formal concepts. Nevertheless, there are a number of fundamental design decisions to take in the VM design. These are motivated and discussed in Sect. 3.

We formulate the VM concept as an extension of the standard concept of module for Java-like (i.e., object-oriented, class-based and strongly typed) languages. To support variability, VMs employ *delta-oriented programming* (DOP) [1, Sect. 6.6.1], [32]. Specifically, we contribute (i) a theoretical foundation of VMs, including formal syntax and semantics, in terms of a core calculus; and (ii) an implementation of VMs as an extension of the ABS language [17, 21].

We choose ABS because it features native implementations of DOP and it was successfully used in industrial case studies for variability modeling [24, 28, 46]. We stress that VMs can be added on top of *any* Java-like language. For instance, a proof-of-concept realization of VM for the Java programming language, based on architectural patterns, is (informally) described in [39]. That paper demonstrates the usefulness of the VM concept, but lacks several VM features introduced here, as well as a formal foundation.

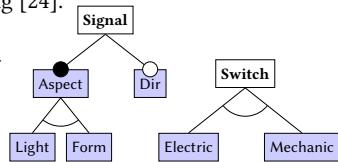
The formal underpinnings of VMs are covered in Sects. 4–7. In Sect. 4 we declare the VM syntax and spell out consistency requirements. Sect. 5 formalizes a statically checkable property of VMs: the *principle of encapsulated variability*, which ensures that any dependency among VMs can be reduced to dependencies among standard variability-free modules. In Sect. 6 we define variant generation in terms of a “flattening” semantics: the variants requested from an SPL represented by a VM, together with necessary variants of other VMs it depends upon, are generated by translating each VM into a set of variability-free, standard modules (one per variant). This results in a variability-free program with suitably disambiguated identifiers and is sufficient to define the semantics of VMs precisely, to compile and to run them. In Sect. 7 we prove soundness of flattening.

Sect. 8 describes how the VM concept is integrated into the existing ABS tool chain. As long as one has control over the parser and abstract syntax tree, it is relatively straightforward to realize the flattening algorithm of Sect. 6 within any compiler tool chain. We evaluate VMs by means of case studies. Related work is discussed in Sect. 9, we conclude in Sect. 10 by outlining ongoing work.

## 2 INTRODUCING VARIABILITY MODULES

We illustrate VMs with an example based on an industrial case study from railway engineering [24].

Our scenario contains signals, switches, interlocking systems, that use multiple variants of signals and switches, and a railway station that uses multiple variants of interlocking systems. Fig. 1 shows the feature models for switches and signals.<sup>1</sup> A signal is either a light signal, using bulbs and colors to indicate the signal aspect or a form signal that uses mechanically moved shapes. All variants of signal have the interface to the interlocking system and basic functionality, such as aspect change, in common (e.g., signals have always the



**Figure 1: Features of Signals and Switches.**

<sup>1</sup>Feature models [8] specify software variants in terms of features. A feature is a name representing some functionality, a set of features is called a configuration, and each variant is identified by a valid configuration (called a product, for short). Equivalent representations of feature models have been proposed in the literature [1, 2], like feature diagrams (Fig. 1) and propositional formulas (lines with keyword `features` in Figs. 2–3).

```

// MODULE HEADER
module Signals; export LSig, CSig, ISig;
features Light, Form, Dir with Light <-> !Form;
configuration KSig = {Dir};
product LSig = {Light};
// CORE PART
unique interface ISig { Bool eqAspect(ISig); Unit setToHalt(); }
class CSig implements ISig { }
// DELTA PART
delta LDelta; adds class CBulb { };
modifies class CSig {
  Unit addBulb() { new CBulb(); };
};
delta FDelta; modifies class CSig { adds Date nextMotorMaintain; };
delta DDelta; adds interface IDir { };
adds class CDir implements IDir { };
modifies class CSig { adds IDir getDirection() { }; };
delta LDelta when Light;
delta FDelta when Form;
delta DDelta when Dir;
  
```

**Figure 2: An SPL of signals as a VM.**

```

// MODULE HEADER
module Switches; export ITrack, CTrack, CSwitch, ISwitch;
features Electric, Mechanic with Electric <-> !Mechanic;
// CORE PART
unique interface ISwitch { }
class CSwitch implements ISwitch { }
unique interface ITrack { ISwitch appendSwitch(); }
class CTrack implements ITrack {
  ISwitch appendSwitch() { ISwitch sw = new CSwitch(); return sw; }
};
// DELTA PART
delta EDelta; modifies class CSwitch {adds Date nextMotorMaintain;};
delta MDelta; modifies class CSwitch {
  adds Bool isMechanic() { return True; }; };
delta EDelta when Electric; delta MDelta when Mechanic;
  
```

**Figure 3: An SPL of tracks and switches as a VM.**

aspects “Halt” and “Go”). If multiple outgoing tracks are possible, a signal may also indicate the direction the train is going—so there are 4 signal variants. Variability shows, for example, in the presence of an additional class `Bulb` in the light signals variant and in the fact that method `setToHalt` (which changes the shown aspect to “Halt”) is different for form signals and light signals (the latter communicate with their `Bulb` instances).

Signals are modeled by the VM `Signals` in Fig. 2. It starts with the *module header*, comprising: the keyword `module`; the module name; the list of exported module elements; the feature list constrained with a propositional formula describing the products; a list of configuration definitions (here just one); and a list of product definitions (here just one), where each definition gives a name to a set of features. Next is the *module core part*, comprising declarations of interface `ISig` and of class `CSig` that implements `ISig`. By default, class and interface definitions can be modified/removed by deltas to obtain different product variants, however, class/interface definitions annotated by the keyword `unique` must be *the same* in all product variants. They enable interoperability between different product variants of the same VM. Finally there is the *delta part*, comprising the deltas that describe the implementation of different variants and their application conditions. Classes and interfaces added by deltas can be modified or removed again by other deltas. The delta `LDelta`, triggered by feature `Light`, adds a class `Bulb` and modifies the class `CSig` to reference the class `Bulb`. Deltas `FDelta` and `DDelta` implement features `Form` and `Dir`, respectively.

Switches and tracks are modeled by the VM in Fig. 3. It is structurally similar to `Signals`. A switch is either electric (controlled from

```

1 // MODULE HEADER
2 module InterlockingSys;
3 export *;
4 import * from Signals; import * from Switches;
5 features Modern, DirOut with True;
6 product PSwitch for Switches =
7   { Modern => {Electric}, !Modern => {Mechanic} }
8 product PSignal for Signals =
9   { DirOut && Modern => {Light,Dir}, Modern => {Light},
10    DirOut && !Modern => {Form,Dir}, !Modern => {Form} }
11 // CORE PART
12 unique interface IILS { }
13 class CILS {
14   Bool testSig() {
15     ISwitch swNormal = new CSwitch() with {Electric};
16     ITrack track = new CTrack() with {Mechanic};
17     ISwitch swNew = track.appendSwitch();
18     ISig sigNormal = new CSig() with LSig;
19     ISig sigShunt = new CSig() with {Form};
20     return sigNormal.eqAspect(sigShunt);
21   }
22   ISwitch createSwitch() { return new CSwitch() with PSwitch; }
23   ISignal createOutSignal() { return new CSignal() with PSignal; }
24   ISignal createInSignal() {
25     return new CSignal() with PSignal - {Dir}; }
26 }

```

Figure 4: An SPL of interlocking systems as a VM.

the interlocking system) or mechanic (controlled locally by a lever). Class `CTrack` contains a reference to class `CSwitch`, which is not declared `unique`. So, even though class `CTrack` is not modified/removed by any delta, its declaration cannot be annotated with `unique`.

Interlocking systems are modeled by the VM in Fig. 4. An interlocking system manages switches and signals that lie on tracks, it imports all the exported elements (feature names are implicitly exported/imported) of the VMs `Signals` and `Switches`. The VM `InterlockingSys` has four variants, modeled by two optional features. Line 6 contains a product definition that gives name `PSwitch` to a product of the VM `Switch`. It is called an *open* product definition, because it depends on the selected product of the VM `InterlockingSys` itself: if feature `Modern` is selected `PSwitch` specifies an electric switch, otherwise it specifies a mechanic switch (product clauses are evaluated in order until a valid one is found). Line 8 contains an open product definition for the VM `Signal`. It is worth observing that open product definitions enable implementing different variants of the VM `InterlockingSys` even without using deltas. Method `testSig` of class `CILS` instantiates classes from two different product variants of `Switches` and from two different product variants of `Signals`. All references to non-`unique` imported classes/interfaces specify a product, by using a `with` clause. In a `with` clause, the product can be specified by explicitly listing its features, by using one of the defined product names, or (more generally) by a set-theoretic expression. For example, `track` is taken from product `{Mechanic}` of module `Switches`, while `sigNormal` uses the product name `LSig` imported from `Signals`. In line 17 a switch is added to a track element: since `track` contains a reference to an instance of the mechanic variant of class `CTrack`, `appendSwitch()` will add a mechanic switch. All signal variants of the VM `Signals` share the same definition of the unique `ISig` interface, thus making it accessible to anyone that imports it from `Signals`. On the other hand, the `CBulb` class is only used inside the VM `Signals`. Different product variants are fully interoperable, as witnessed by the expression in line 20.

A VM that does not contain a feature model (and, therefore, no configuration definitions, no open product definitions and no deltas) is called a *variability-free module* (VFM). All classes of a

```

module RailwayStation;
import * from InterlockingSys;
init {
  IILS ils1 = new CILS() with { DirOut };
  IILS ils2 = new CILS() with { Modern };
}

```

Figure 5: Railway station as a main module.

VFM are considered unique (there is no need to write the `unique` keyword). Each program must have exactly one *main* module: a VFM containing an implicit class providing an initialization method declared by the keyword `init`. The whole railway station is modeled by a main module, given in Fig. 5, together with the VM `Signals` in Fig. 2, the VM `Switches` in Fig. 3, and the VM `InterlockingSys` in Fig. 4. It represents a MPL—we call it the railway station MPL.

### 3 DESIGN DECISIONS

Below we briefly illustrate the rationale behind the major VM design decisions.

**Unique Annotation.** As explained above, `unique` class/interface declarations in a VM  $M$  are shared by all variants of  $M$ . Without the `unique` keyword, unique class/interface declarations should be inferred (cf. Def. 7.1, Thm. 7.1 below), thus creating the danger of unintended changes of the set of unique classes/interfaces in a program. Obviously, a tool that points out all class/interface declarations that *could* be annotated `unique` would be useful.

**Principle of Encapsulated Variability (PEV).** The PEV prescribes that each VM can depend on other VMs only by using classes or interfaces that are either `unique` or that belong to a *specific* variant. If a VM program adheres to the PEV, then flattening (defined in Sect. 6)—which removes variability and generates those variants required by the dependencies—can resolve all dependencies among VMs to dependencies among VFM. The main reasons for adopting the PEV are *simplicity* and *usability*: it suffices to work with a standard module concept (no need for composition or disambiguation operators as, for example, [26]) and it is easy for the modeler to find out to which implementation any object reference in a VM refers to.

**Local Feature Model.** Each VM has its own feature model disjoint from those of other VMs: each feature name is *local* to the VM where it is declared, and there is no global name space for features. It might be useful to add support for expressing constraints connecting the local feature models (e.g., to specify that certain variants must not co-exist in the same application).

**Implicit Export/Import Flattening.** Each VM  $M$  must declare the union of the exports/imports of all its variants. Then the flattening generates the export/import clauses of each variant by dropping export clauses for classes/interfaces not present in that variant, and by creating the import clauses for the required variants of the VMs mentioned in the import clauses of  $M$ . This design choice avoids the need to define delta operations on export/import clauses in the language that then would be supplied by the modeler.<sup>2</sup> Altogether,

<sup>2</sup>To extend VMs with delta operations on export clauses is straightforward. It would allow sometimes to shorten export clauses. On the other hand, since implicit flattening drops all unused imports, deltas on import clauses provide no advantage.

$\text{Prg} ::= \overline{\text{Mdl}}$	<b>Program</b>
$\text{Mdl} ::= \overline{\text{MdlH}} \overline{\text{MdlC}} \overline{\text{MdlD}}$	(Variability) Module
$\overline{\text{MdlH}} ::= \text{module } M; [\text{export } \text{tc};]$ $\quad \text{import } \text{tc from } M; [\text{features } \overline{F} \text{ with } \Phi; \overline{\text{KD}}] \overline{\text{PD}}$	<b>Module Header</b>
$\text{tc} ::= \text{tn } \overline{\text{tn}} \mid *$	Trade Clause
$\text{tn} ::= C \mid I \mid K \mid P$	Traded names
$\text{KD} ::= \text{configuration } K = \text{KE}$	Configuration Declaration
$\text{KE} ::= K \mid P \mid \{ \overline{F} \} \mid \text{KE} + \text{KE} \mid \text{KE} * \text{KE} \mid \text{KE} - \text{KE}$	Configuration Expression
$\text{PD} ::= \text{product } P [\text{for } M] = \text{KE}$ $\quad \mid \text{product } P [\text{for } M] = \{ \text{PC}, \overline{\text{PC}} \}$	Closed Product Declaration Open Product Declaration
$\text{PC} ::= \Phi \Rightarrow \text{KE}$	Pattern Clause
$\overline{\text{MdlC}} ::= \overline{\text{Defn}} [\text{init } \{ \overline{S} \}]$	<b>Module Core Part</b>
$\overline{\text{Defn}} ::= [\text{unique}] \text{ID} \mid [\text{unique}] \text{CD}$	Interface/Class Definition
$\text{ID} ::= \text{interface } I [\text{extends } \text{IR } \overline{\text{IR}}] \{ \overline{\text{MH}} \}$	<b>Interface Definition</b>
$\text{IR} ::= I [\text{with } \text{KE}] \mid \text{M.I} [\text{with } \text{KE}]$	Interface Reference
$\text{MH} ::= T \text{ m} ( \overline{T} \overline{x} )$	Method Header
$T ::= \text{IR} \mid \text{Unit} \mid \text{Int} \mid \dots$	Type
$\text{CD} ::= \text{class } C [\text{implements } \text{IR } \overline{\text{IR}}] \{ \overline{\text{FD}} \overline{\text{MD}} \}$	<b>Class Definition</b>
$\text{FD} ::= T \text{ f};$	Field Definition
$\text{MD} ::= \text{MH} \{ \overline{S} \text{return } E; \}$	Method Definition
$S ::= [T] \text{ v} = E; \mid E. \text{f} = E; \mid \dots$	Statement
$E ::= x \mid E. \text{f} \mid E. \text{m}(\overline{E}) \mid \text{new } \text{CR}() [\text{with } \text{KE}] \mid \dots$	Expression
$\text{CR} ::= C \mid \text{M.C}$	Class Reference
$\overline{\text{MdlD}} ::= \overline{\text{Dlt}} \text{CK}$	<b>Module Delta Part</b>
$\overline{\text{Dlt}} ::= \text{delta } D; \overline{\text{CO}} \overline{\text{IO}}$	<b>Delta</b>
$\text{CO} ::= \text{adds } \text{CD} \mid \text{removes class } C$ $\quad \mid \text{modifies class } C [\text{adds } \text{IR } \overline{\text{IR}}] [\text{removes } \text{IR } \overline{\text{IR}}] \{ \overline{\text{AO}} \}$	Class Operation
$\text{AO} ::= \text{adds } \text{AD} \mid \text{removes } \text{HD} \mid \text{modifies } \text{MD}$	Attribute Operation
$\text{AD} ::= \text{FD} \mid \text{MD}$	Attribute Declaration
$\text{HD} ::= \text{FD} \mid \text{MH}$	Header Declaration
$\text{IO} ::= \text{adds } \text{ID} \mid \text{removes interface } I$ $\quad \mid \text{modifies interface } I [\text{adds } \text{IR } \overline{\text{IR}}] [\text{removes } \text{IR } \overline{\text{IR}}] \{ \overline{\text{SO}} \}$	Interface Operation
$\text{SO} ::= \text{adds } \text{MH} \mid \text{removes } \text{MH}$	Signature Operation
$\text{CK} ::= \text{DAC } \overline{\text{DAO}}$	<b>Configuration Knowledge</b>
$\text{DAC} ::= \text{delta } D \text{ when } \Phi;$	Delta Activation Condition
$\text{DAO} ::= D \overline{\text{D}} < D \overline{\text{D}} < D \overline{\text{D}};$	Delta Application Order

Figure 6: ABS-VM abridged syntax.

it reduces the cognitive burden to understand VM code and the effort to write it.

**Family-based checking.** VM are designed to permit family-based analysis [15, 42, 43]. The implementation of VM as part of the ABS compiler tool chain (Sect. 8) checks PEV before flattening. Moreover, we are currently implementing a family-based analysis to check—before flattening—whether a program  $\text{Prg}$  is delta-application sound (thus ensuring, according to Thm. 7.4, that flattening will succeed), whether the generated VFM will be well-typed, and, more generally, whether the variants of the VMs in  $\text{Prg}$  as a whole (including those not generated by flattening  $\text{Prg}$ ) would form a well-typed VFM.

## 4 SYNTAX OF ABS VARIABILITY MODULES

The abridged syntax of *ABS with VMs* (ABS-VM, for short) is given in Fig. 6. It defines the OO fragment of ABS [17, 21], extended with VM concepts. A program is a sequence of VMs—as usual,  $\overline{X}$  denotes a possibly empty finite sequence of elements  $X$ . A VM consists of a header ( $\overline{\text{MdlH}}$ ), a core part ( $\overline{\text{MdlC}}$ ), and a delta part ( $\overline{\text{MdlD}}$ ). A VM header comprises the keyword `module` followed by the name of the

VM, by some (possibly none) `import` and `export` clauses (listing the class/interface/configuration/product names, respectively, that are exported or imported by the VM), by the optional definition of a feature model (where  $\overline{F}$  are the features and  $\Phi$  is a propositional formula over features), by a list of configuration definitions and by a list of product definitions. A configuration expression  $\text{KE}$  is a set-theoretic expression over sets of features ( $+$ ,  $*$  and  $-$  denote union, intersection and difference, respectively). A product definition  $\text{PD}$  is *closed* if it is of the form `product P [for M] = KE`, otherwise it is *open*. The clauses in an open product definition are examined in sequence until the first valid clause is found. The right-hand sides of configuration definitions do not contain product names, and the right-hand sides of closed product definitions do not contain open product names. Recursive configuration/product definitions are forbidden.

Both the module core part and the module delta part may be empty. A module core part comprises a sequence of class and interface definitions  $\overline{\text{Defn}}$ . As an extension to ABS syntax, each of these definitions may be prefixed by the keyword `unique`. Each use of a class, interface or product name imported from another module may be prefixed by the name of the module—the name of the module *must* be used if there are ambiguities (for example, when an interface with name  $\text{I}$  is imported from two different modules). Moreover, each use of a non-unique class or interface imported from another module must be followed by a `with`-clause, specifying (by means of a configuration expression) the variant of the VM it is taken from. From now on, we consider only ABS-VM programs containing one main module (as in the final paragraph of Sect. 2) such that any other VM does not contain the keyword `init`. Observe that a VFM (as defined in the final paragraph of Sect. 2) without a product definition (a VFM may contain closed product definitions) and no occurrences of the `with` keyword is a variability-free *ABS* module.

The module delta part comprises a sequence of delta definitions  $\overline{\text{Dlt}}$  followed by configuration knowledge  $\text{ck}$ . Each delta specifies a number of changes to the module core part. A delta comprises the keyword `delta` followed by the name of the delta, by a sequence of class operations  $\overline{\text{CO}}$  and by a sequence of interface operations  $\overline{\text{IO}}$ . An *interface operation* can add or remove an interface definition, or modify it by adding/removing names to the list of the extended interfaces or by adding/removing method headers. A *class operation* can add or remove a class definition, or modify it by adding/removing names to the list of the implemented interfaces, by adding/removing fields or by adding/removing/modifying methods. Modifying a method means to replace its body with a new body. The new body may call the reserved method name `original`, which during delta application is bound to the previous implementation of the method.

Configuration knowledge  $\text{ck}$  provides a mapping from products to variants by describing the connection between deltas and features: it specifies an activation condition  $\Phi$  (a propositional formula over features) for each delta  $\text{D}$  by means of a `DAC` clause; and it specifies an application ordering between deltas by means of a sequence of `DAO` clauses. Each `DAO` clause specifies a partial order over the set of deltas in terms of a total order on disjoint subsets of delta names—a `DAO` clause allows developers to express (as a partial order) dependencies between the deltas (which are usually semantic “requires” relations [4]). The overall delta application order is the union of these partial orders—the compiler checks that the resulting relation

$R$  represents a specification that is *consistent* (i.e.,  $R$  is a partial order) and *unambiguous* (i.e., all the total delta application orders that respect  $R$  generate the same variant for each product). Techniques for checking that  $R$  is unambiguous are described in the literature [4, 27].

The following definition of normal form formalizes a minimum consistency requirement on ABS-VM programs.

**Definition 4.1 (ABS-VM Normal Form).** An ABS-VM program  $\text{Prg}$  is in *normal form* if all its VMs  $\mathcal{M}$  satisfy the following conditions:

- (1) All class references  $\text{CR}$  and interface references  $\text{IR}$  occurring in  $\mathcal{M}$  are qualified, that is of the form  $\mathcal{M}'.N$  for some module name  $\mathcal{M}'$  and class/interface name  $N$ , and if  $\mathcal{M}' \neq \mathcal{M}$  then  $\mathcal{M}$  contains the import clause `import N from  $\mathcal{M}'$ .`
- (2) If  $\mathcal{M}$  contains a clause `import tc from  $\mathcal{M}'$`  then  $\mathcal{M}' \neq \mathcal{M}$  and all traded names in `tc` occur in the export clause of  $\mathcal{M}'$ . No open product names are exported.
- (3) Let  $\mathcal{M}$  contain a definition
  - (a) `configuration K = KE`. Then: (i) all feature names occurring in `KE` are features of  $\mathcal{M}$  and all configuration names occurring in `KE` have been already defined in  $\mathcal{M}$ ; and (ii) no product name occurs in `KE`.
  - (b) `product P = KE` then: (i) condition (3a).(i) above holds; (ii) all product names occurring in `KE` have been already defined in  $\mathcal{M}$  and are closed; and (iii) `KE` denotes a product of  $\mathcal{M}$ .
  - (c) `product P for  $\mathcal{M}' = KE$` . Then: (i)  $\mathcal{M} \neq \mathcal{M}'$ ; (ii) all feature names occurring in `KE` are features of  $\mathcal{M}'$  and all configuration/product names occurring in `KE` are imported from  $\mathcal{M}'$ ; and (iii) `KE` denotes a product of  $\mathcal{M}'$ .
  - (d) `product P for  $\mathcal{M}' = \{\Phi_1 \Rightarrow KE_1, \dots, \Phi_n \Rightarrow KE_n\}$  ( $n \geq 1$ )`. Then: (i)  $\mathcal{M} \neq \mathcal{M}'$ ; (ii) for all  $1 \leq j \leq n$ , all configuration/product names occurring in `KEj` are imported from  $\mathcal{M}'$ ; (iii) for all  $1 \leq j \leq n$ , all feature names occurring in  $\Phi_j$  are features of  $\mathcal{M}$ , all feature names occurring in `KEj` are features of  $\mathcal{M}'$ , at least one product of  $\mathcal{M}$  satisfies  $(\bigwedge_{1 \leq i < j} \neg \Phi_i) \wedge \Phi_j$ , and `KEj` denotes a product of  $\mathcal{M}'$ ; and (iv) all products of  $\mathcal{M}$  satisfy  $\bigvee_{1 \leq i \leq n} \Phi_i$ .
  - (e) `product P = \{\Phi_1 \Rightarrow KE_1, \dots, \Phi_n \Rightarrow KE_n\} ( $n \geq 1$ )`. Then: (i) for all  $1 \leq j \leq n$ , all configuration/product names occurring in `KEj` have been already defined in  $\mathcal{M}$ ; (ii) the condition obtained from condition (3d).(iii) above by replacing  $\mathcal{M}'$  by  $\mathcal{M}$  holds; and (iii) condition (3d).(iv) above holds.
- (4) If  $\mathcal{M}$  contains an occurrence of `new  $\mathcal{M}'$ .C() with KE` or  `$\mathcal{M}'$ .I with KE`, then: (i) all feature names occurring in `KE` are features of  $\mathcal{M}'$ ; (ii) if  $\mathcal{M}' = \mathcal{M}$  then all configuration/product names occurring in `KE` are defined in  $\mathcal{M}$ ; (iii) if  $\mathcal{M}' \neq \mathcal{M}$  then all configuration/product names occurring in `KE` are either imported from  $\mathcal{M}'$  or defined in  $\mathcal{M}$  by a declaration of the form `product P for  $\mathcal{M}' = \dots$` ; and (iv) `KE` denotes a product of  $\mathcal{M}'$ .

Checking whether a program can be transformed into normal form (and, if so, doing it) is straightforward—for each VM  $\mathcal{M}$ : conditions (1), (3a), (3b), (3e) and (when  $\mathcal{M}' = \mathcal{M}$ ) condition (4) can be ensured by inspecting only  $\mathcal{M}$ ; condition (2) and (when  $\mathcal{M}' \neq \mathcal{M}$ ) condition (4) can be ensured by inspecting only  $\mathcal{M}$  and the header of the modules  $\mathcal{M}'$  mentioned in the import clause of  $\mathcal{M}$ . Conditions (3b).(iii), (3c).(iii), (3d).(iii), (3d).(iv) and (4).(iv) can be checked with a SAT solver [41]. Programs that cannot be transformed into normal form are rejected by the compiler.

## 5 ENCAPSULATED VARIABILITY

In this section we formalize the principle of encapsulated variability. We only consider programs in normal form (Def. 4.1). To formalize and to implement automated checking of PEV adherence we introduce the notion of dependency and the functions `CORE`, `UNIQUE`, and `BASE`.

**Definition 5.1 (Dependency).** A VM  $\mathcal{M}'$  *depends on* a VM  $\mathcal{M}$  if  $\mathcal{M}'$  contains an occurrence of  $\mathcal{M}.N$  where  $N$  is a class/interface name. An occurrence of  `$\mathcal{M}.I$  with KE` or `new  $\mathcal{M}.C()$  with KE` is called *with-dependency* (on  $\mathcal{M}.I$  or  $\mathcal{M}.C$ , respectively), while an occurrence of  `$\mathcal{M}.I$`  or `new  $\mathcal{M}.C(\dots)$`  (i.e. not followed by a `with`) is called *with-free-dependency* (on  $\mathcal{M}.I$  or  $\mathcal{M}.C$ , respectively). An occurrence of  `$\mathcal{M}.I$  with KE` or  `$\mathcal{M}.C()$  with KE` is called *with-open-dependency* if `KE` contains an occurrence of an open product name  $P$ , it is called *with-closed-dependency* else.

**Definition 5.2 (Functions `CORE`, `UNIQUE`, `BASE`).** Given a program  $\text{Prg}$ ; for all VMs  $\mathcal{M}$  of  $\text{Prg}$ : `CORE( $\text{Prg}, \mathcal{M}$ )` is the set of qualified names  $\mathcal{M}.N$  of all interfaces/classes  $N$  whose definition occurs in the core part of  $\mathcal{M}$ ; `UNIQUE( $\text{Prg}, \mathcal{M}$ )`  $\subseteq$  `CORE( $\text{Prg}, \mathcal{M}$ )` contains those class/interface names whose declaration is annotated with `unique`; `BASE( $\text{Prg}, \mathcal{M}$ )`  $\subseteq$  `CORE( $\text{Prg}, \mathcal{M}$ )` contains those class/interface names that are modified, removed or added by some delta of  $\mathcal{M}$ .

Now we can formalize the PEV as follows:

**Definition 5.3 (Principle of Encapsulated Variability (PEV)).** A program  $\text{Prg}$  (in normal form) adheres to PEV, if for all VMs  $\mathcal{M}$  of  $\text{Prg}$ :

- (1) `UNIQUE( $\text{Prg}, \mathcal{M}$ )`  $\cap$  `BASE( $\text{Prg}, \mathcal{M}$ )` =  $\emptyset$ .
- (2) For all  $\mathcal{M}.N \in$  `UNIQUE( $\text{Prg}, \mathcal{M}$ )` the definition `Defn` of  $N$  (in the core part `mdlC` of  $\mathcal{M}$ ) does not contain *with-open-dependencies* and, for all *with-free-dependencies* on  $\mathcal{M}.N'$  occurring in `Defn`, it holds that  $\mathcal{M}.N' \in$  `UNIQUE( $\text{Prg}, \mathcal{M}$ )`.
- (3) For all *with-free-dependencies* on  $\mathcal{M}'.N$  occurring in  $\mathcal{M}$ : if  $\mathcal{M}' \neq \mathcal{M}$  then  $\mathcal{M}'.N \in$  `UNIQUE( $\text{Prg}, \mathcal{M}'$ )`.

To check whether a program adheres to the PEV is straightforward. Programs that do not adhere to the PEV are rejected by the compiler. According to the PEV, VMs can support two types of interaction among variants:

**Variant interoperability.** Different variants of the *same* VM can co-exist and cooperate via unique classes/interfaces. For instance, in the interlocking system MPL of Sect. 2, all *interfaces* are unique and all *classes* are not unique (which is a common pattern). Then, in line 20 of Fig. 4, an instance of class `CSig` in the variant of VM `Signal` for product `{Light}` receives an invocation of method `eqAspect` that (accepts an argument of type `Signal` as formal parameter and) takes as parameter an instance of `CSig` in the variant of `Signal` for product `{Form}`.

**Variant interdependence.** The code of a variant of a VM  $\mathcal{M}_1$  can depend on the code of a variant of a VM  $\mathcal{M}_2$  (and possibly vice versa). I.e., the code of  $\mathcal{M}_1$  refers to unique classes/interfaces of  $\mathcal{M}_2$  (via *with-free-dependencies*) or to classes/interfaces of a specific variant of  $\mathcal{M}_2$  (via *with-dependencies*). A special case of variant interdependence is when  $\mathcal{M}_1 = \mathcal{M}_2$ , i.e.,  $\mathcal{M}_1$  has a *with-dependency* on a class/interface of  $\mathcal{M}_1$  itself. Then in the flattened program a variant of  $\mathcal{M}_1$  will contain an occurrence of a class/interface name that is declared in a different variant of  $\mathcal{M}_1$ .

## 6 SEMANTICS OF VARIABILITY MODULES

In this section, we assume (without loss of generality): (i) the considered program  $\text{Prg}$  is in normal form and adheres to the PEV; (ii) all configuration definitions  $\text{kd}$  and closed product definitions  $\text{pd}$  have been resolved in  $\text{Prg}$ , i.e. all occurrences of their names are removed from export/import clauses of  $\text{Prg}$ , and all their remaining occurrences in  $\text{Prg}$  were replaced with their value (a set of features).

In Sect. 6.1 we introduce auxiliary functions for the extraction of relevant information from ABS-VM programs. Then, in Sect. 6.2 we give rewrite rules for transforming an ABS-VM program into a variability-free ABS program.

### 6.1 Auxiliary Functions

*Definition 6.1 (Lookup Functions).* Given a VM  $\mathfrak{M}$  of  $\text{Prg}$  we define the sets:

- $\text{mdlUnique}(\text{Prg}, \mathfrak{M})$  for the interface/class definitions  $\overline{\text{Defn}}$  in the Module Core Part  $\text{Mdlc}$  of  $\mathfrak{M}$  annotated with  $\text{unique}$ .
- $\text{mdlNotUnique}(\text{Prg}, \mathfrak{M})$  for the interface/class definitions not in  $\text{mdlUnique}(\text{Prg}, \mathfrak{M})$ .
- $\text{mdlInit}(\text{Prg}, \mathfrak{M})$  for the init block of  $\mathfrak{M}$ , if it exists, or the empty sequence otherwise; also  $\text{mdlInit}(\text{Prg})$  for the name  $\mathfrak{M}$  of the VM such that  $\text{mdlInit}(\text{Prg}, \mathfrak{M})$  is not the empty sequence.
- $\text{mdlDelta}(\text{Prg}, \mathfrak{M}, \pi)$  where  $\pi$  is a product of  $\mathfrak{M}$ , for any ordered sequence  $\overline{\text{Dlt}}$  containing exactly those deltas of  $\mathfrak{M}$  that are activated by  $\pi$ , respecting the order among deltas specified in the configuration knowledge of  $\mathfrak{M}$ .

The meaning of  $\text{with}$ -free-dependencies or open  $\text{with}$ -dependencies  $\delta$  occurring in a VM  $\mathfrak{M}$  is relative to the product  $\pi$  of  $\mathfrak{M}$  being considered. We say a dependency  $\delta$  is *ground* to mean that it is either  $\text{with}$ -free or the configuration expression  $\text{ke}$  in its  $\text{with}$ -clause is a set of features  $\pi = \{F_1, \dots, F_n\}$  ( $n \geq 0$ ). The following definition introduces notations for extracting the meaning of ground dependencies occurring in the core part of a given VM of a given program.

*Definition 6.2 (Ground Dependency Meaning).* Given a program  $\text{Prg}$ , a VM  $\mathfrak{M}$  of  $\text{Prg}$ , a ground dependency  $\delta$  on  $\mathfrak{M}.N$  occurring in  $\mathfrak{M}$ , let  $xc$  be either the symbol  $\perp$  or a product  $\pi$  of  $\mathfrak{M}$ . We define:

$$\Downarrow(\text{Prg}, \mathfrak{M}, \delta, xc) = \begin{cases} (\mathfrak{M}', \perp) & \text{when } \mathfrak{M}.N \in \text{UNIQUE}(\text{Prg}, \mathfrak{M}') \\ (\mathfrak{M}', xc) & \text{when } \mathfrak{M}' = \mathfrak{M}, \delta \text{ is } \text{with}\text{-free and } \mathfrak{M}.N \notin \text{UNIQUE}(\text{Prg}, \mathfrak{M}) \\ (\mathfrak{M}', \pi) & \text{when } \delta \text{ is } \mathfrak{M}.N \text{ with } \pi \text{ and } \mathfrak{M}.N \notin \text{UNIQUE}(\text{Prg}, \mathfrak{M}') \end{cases}$$

Let all the dependencies occurring in the core part  $\text{Mdlc}$  of  $\mathfrak{M}$  be ground. Then  $\Downarrow(\text{Prg}, \mathfrak{M}, \text{Mdlc}, xc) = \{\Downarrow(\text{Prg}, \mathfrak{M}, \delta, xc) \mid \delta \text{ is a dependency in } \text{Mdlc}\}$ .

Flattening a program  $\text{Prg}$  may require to generate more than one variant for each of its VMs. The flattening process generates new names for the generated variability-free ABS modules implementing the required variants, and translates the dependencies occurring in  $\text{Prg}$  to suitable dependencies using the generated names. The following definition introduces notations for the names of the generated modules and the translation of  $\text{with}$ - and  $\text{with}$ -free-dependencies into the corresponding dependencies among non-variable ABS modules.

*Definition 6.3 (New Module Name, Dependency Translation).* Given a program  $\text{Prg}$ , a VM  $\mathfrak{M}$  of  $\text{Prg}$ , let  $xc$  be either  $\perp$  or a product  $\pi$  of  $\mathfrak{M}$ . We denote by  $\Uparrow(\mathfrak{M}, xc)$  the name of the module that implements the

unique part of the variants of  $\mathfrak{M}$  if  $xc = \perp$ , or the name of the module that implements the non-unique part of the variant of  $\mathfrak{M}$  for product  $\pi$ . Moreover, given a ground dependency  $\delta$  on  $\mathfrak{M}.N$ , we define:

$$\Uparrow(\text{Prg}, \mathfrak{M}, \delta, xc) = \begin{cases} \Uparrow(\mathfrak{M}', \perp).N & \text{when } \mathfrak{M}.N \in \text{UNIQUE}(\text{Prg}, \mathfrak{M}') \\ \Uparrow(\mathfrak{M}', xc).N & \text{when } \mathfrak{M}' = \mathfrak{M}, \delta \text{ is } \text{with}\text{-free and } \mathfrak{M}.N \notin \text{UNIQUE}(\text{Prg}, \mathfrak{M}) \\ \Uparrow(\mathfrak{M}', \pi).N & \text{when } \delta \text{ is } \mathfrak{M}.N \text{ with } \pi \text{ and } \mathfrak{M}.N \notin \text{UNIQUE}(\text{Prg}, \mathfrak{M}') \end{cases}$$

Let all the dependencies occurring in the core part  $\text{Mdlc}$  of  $\mathfrak{M}$  be ground. Then we define  $\Uparrow(\text{Prg}, \mathfrak{M}, \text{Mdlc}, xc)$  as the VM core  $\text{Mdlc}'$  obtained from  $\text{Mdlc}$  by replacing each dependency  $\delta$  occurring in it with  $\Uparrow(\text{Prg}, \mathfrak{M}, \delta, xc)$ .

### 6.2 Flattening

The following definition formalizes the application of an ordered sequence of deltas  $\overline{\text{Dlt}}$  (the deltas activated by a product  $\pi$  of a VM  $\mathfrak{M}$ ) to a sequence  $\overline{\text{Defn}}$  of interface/class definitions (the non-unique class/interface definitions in the module core part  $\text{Mdlc}$  of  $\mathfrak{M}$ ).

*Definition 6.4 (Delta Application).* Given a sequence of declarations  $\overline{\text{Defn}}$  and an ordered sequence of deltas  $\overline{\text{Dlt}}$ , we denote with the relation  $(\overline{\text{Dlt}}, \overline{\text{Defn}}) \rightarrow^* \overline{\text{Defn}'}$  that  $\overline{\text{Defn}'}$  is the outcome of the procedure described in App. A.

For all VMs  $\mathfrak{M}$  of  $\text{Prg}$ , if the products  $\pi$  of  $\mathfrak{M}$  are given, then the right-hand side of each open product definition  $\text{product } P = \dots$  or  $\text{product } P \text{ for } M' = \dots$  in  $\mathfrak{M}$  can be evaluated to a product. This induces a mapping  $\sigma = \text{genP}(\text{Prg}, \mathfrak{M}, \pi)$  from open product names to products. Given a sequence of interface/class definitions  $\overline{\text{Defn}}$  and such a mapping  $\sigma$ , for at least the open product names occurring in  $\overline{\text{Defn}}$  to products, denote with  $\sigma(\overline{\text{Defn}})$  the definitions obtained from  $\overline{\text{Defn}}$  by replacing each occurrence of an open product name  $P$  with  $\sigma(P)$ .

*Definition 6.5 (Grounding with-clauses).* Given a Module Core Part  $\text{Mdlc}$  that does not contain occurrences of product names, we write  $\text{Mdlc} \rightsquigarrow^* \text{Mdlc}'$  to mean that the module core part  $\text{Mdlc}'$  has been obtained from  $\text{Mdlc}$  by replacing the right-hand side of each  $\text{with}$ -clause (which is a set-theoretic expression over sets of features) by the corresponding set of features (which, since the overall program is assumed in normal-form, is a product).

We are ready to define the rules that flatten a VM:

*Definition 6.6 (Flattening a VM).* Let  $\mathfrak{M}$  be the name of a VM of  $\text{Prg}$ , let  $xc$  be either the symbol  $\perp$  or a product  $\pi$  of  $\mathfrak{M}$ . The following rules define a judgment of the form  $\mathfrak{M} \xrightarrow{\text{Prg}, xc} D, \text{Mdl}$  where:  $\text{Mdl}$  is the code of a variability-free ABS module named  $\Uparrow(\mathfrak{M}, xc)$ , which, for the case  $xc = \perp$  implements the unique part of the variants of  $\mathfrak{M}$ , for the case  $xc = \pi$  implements the non-unique part of the variant of  $\mathfrak{M}$  for product  $\pi$ . Moreover,  $D$  is a set that identifies the variability-free ABS modules that  $\Uparrow(\mathfrak{M}, xc)$  depends upon.

$$\frac{\text{mdlUnique}(\text{Prg}, \mathfrak{M}) = \overline{\text{Defn}} \quad \overline{\text{Defn}} \text{ mdlInit}(\text{Prg}, \mathfrak{M}) \rightsquigarrow^* \text{Mdlc} \quad \Downarrow(\text{Prg}, \mathfrak{M}, \text{Mdlc}, \perp) = D = \{(M_i, xc_i) \mid i \in I\}}{\mathfrak{M} \xrightarrow{\text{Prg}, \perp} D, \text{module } \Uparrow(\mathfrak{M}, \perp); \text{export } *; \text{import } * \text{ from } \Uparrow(\{M_i, xc_i\}) \Uparrow(\text{Prg}, \mathfrak{M}, \text{Mdlc}, \perp)}$$

$$\frac{\text{mdlNotUnique}(\text{Prg}, \mathfrak{M}) = \overline{\text{Defn}} \quad \text{mdlDelta}(\text{Prg}, \mathfrak{M}, \pi) = \overline{\text{Dlt}} \quad (\overline{\text{Dlt}}, \overline{\text{Defn}}) \rightarrow^* \overline{\text{Defn}'} \quad \sigma = \text{genP}(\text{Prg}, \mathfrak{M}, \pi) \quad \sigma(\overline{\text{Defn}'}) \rightsquigarrow^* \overline{\text{Defn}''} \quad \Downarrow(\text{Prg}, \mathfrak{M}, \overline{\text{Defn}'}, \perp) = D = \{(M_i, xc_i) \mid i \in I\}}{\mathfrak{M} \xrightarrow{\text{Prg}, \pi} D, \text{module } \Uparrow(\mathfrak{M}, \pi); \text{export } *; \text{import } * \text{ from } \Uparrow(\{M_i, xc_i\}) \Uparrow(\text{Prg}, \mathfrak{M}, \overline{\text{Defn}'}, \pi)}$$

The first rule generates a module implementing the unique part of the variants of a given VM  $m$ . To do so, it extracts the unique part  $\text{Defn}$  of the VM, its optional init block, and the dependencies  $D$  occurring in these parts. The rule returns the set of dependencies  $D$  (which identifies variability-free ABS modules that need to be generated) and a new variability-free ABS module named  $\uparrow(m, \perp)$  that: (i) exports everything; (ii) imports from all variability-free ABS modules identified in  $D$ ; and (iii) contains the unique classes/interfaces of the original VM, where all syntactic dependencies have been translated according to  $\uparrow$ .

The second rule generates a variability-free ABS module implementing the non-unique part of the variant of the VM  $m$  for the product  $\pi$ . It is similar to the first rule, except for two elements: (i) the optional init block is not considered (it cannot be present); (ii) the extracted (non-unique classes/interfaces) part of the VM is modified by applying the activated deltas as described in Def. 6.4 before being integrated in the resulting module. The next definition gives the rewrite rules for flattening a whole ABS-VM program.

*Definition 6.7 (Flattening an ABS-VM program).* Let  $\varepsilon$  denote the empty program, representing the initial partial result of flattening an ABS-VM program  $\text{Prg}$ . The rules define a judgment of the form  $\text{Prg}' , A_1, D_1 \xrightarrow{\text{Prg}} \text{Prg}' , A_2, D_2$ , where:  $\text{Prg}'$  (either  $\varepsilon$  or a variability-free ABS program) is a partial result of the flattening of  $\text{Prg}$ ; the set  $A_1$  identifies the already generated variability-free ABS modules; the set  $D_1$  identifies the variability-free ABS modules that must be generated to fulfill the dependencies in  $\text{Prg}'$ ; the variability-free ABS program  $\text{Prg}'$  is obtained by adding to  $\text{Prg}'$  the code of one of the variability-free ABS modules identified by  $D_1$ ; the sets  $A_2$  and  $D_2$  are obtained by suitably updating  $A_1$  and  $D_1$ , respectively. Let  $\xrightarrow{\text{Prg}^*}$  be the transitive closure of  $\xrightarrow{\text{Prg}}$ . The flattening of ABS-VM program  $\text{Prg}$  is the variability-free ABS program  $\text{Prg}'$  such that  $\varepsilon, \emptyset, \emptyset \xrightarrow{\text{Prg}^*} \text{Prg}' , A, \emptyset$  holds.

$$\frac{\text{mdllnit}(\text{Prg}) = M \quad M \xrightarrow{\text{Prg}, \perp} D, \text{Md1} \quad A = \{(M, \perp)\}}{\varepsilon, \emptyset, \emptyset \xrightarrow{\text{Prg}} \text{Md1}, A, (D \setminus A)}$$

$$\frac{\text{Prg}' \neq \varepsilon \quad (M, xc) \in D_1 \quad M \xrightarrow{\text{Prg}, xc} D, \text{Md1} \quad A_2 = A_1 \cup \{(M, xc)\} \quad D_2 = (D_1 \cup D) \setminus A_2}{\text{Prg}' , A_1, D_1 \xrightarrow{\text{Prg}} \text{Prg}' , \text{Md1}, A_2, D_2}$$

The sets  $A$  and  $D$  above refer to dependencies in the original program  $\text{Prg}$ . The first rule starts with the empty ABS program and dependency sets, adds the ABS module implementing the (unique part of the) main module of  $\text{Prg}$  and updates the dependency sets. The second rule extends  $\text{Prg}'$  by adding the ABS module required by one of the dangling dependency in  $D_1$ , and replaces the dependency sets  $A_1$  and  $D_1$  by their updated versions  $A_2$  and  $D_2$ .

## 7 PROPERTIES OF VARIABILITY MODULES

The following definition and theorem show that one can automatically infer the maximal set of class/interface declarations that can soundly be annotated with **unique**.

*Definition 7.1 (Function MaxUNIQUE).* For every program  $\text{Prg}$ , for all VM  $m$  of  $\text{Prg}$ , let  $S_m = \text{CORE}(\text{Prg}, m) \setminus \text{BASE}(\text{Prg}, m)$  and define  $F_m : (2^{S_m}, \subseteq) \rightarrow (2^{S_m}, \subseteq)$  to be the non-increasing monotone function such that:  $F_m(X)$  is the subset of  $X$  obtained by removing simultaneously all classes/interfaces  $m.N$  such that the definition

of  $m$  in the core part of  $m$  contains a **with-free-dependency** on a class/interface  $m.N' \notin X$  or contains a **with-open-dependency**. Then  $\text{MaxUNIQUE}(\text{Prg}, m)$  is the set computed by iterating  $F_m(X)$  on  $S_m$  until a fixpoint is reached, i.e., the set  $U = F_m^n(S_m)$  such that  $U = F_m(U)$  for some  $n \geq 0$ .

Observe that  $\text{MaxUNIQUE}(\text{Prg}, m)$  is computed locally on the VM  $m$  and always terminates (since  $F_m$  is non-increasing monotone and  $S_m$  is finite). Unfortunately, a program  $\text{Prg}'$  such that, for all VM  $m$  of  $\text{Prg}'$ ,  $\text{UNIQUE}(\text{Prg}', m) = \text{MaxUNIQUE}(\text{Prg}', m)$  may not adhere to the PEV, because of item (3) in Def. 5.3. However, by the following theorem, if such a  $\text{Prg}'$  does not adhere to the PEV, then *any* program obtained from  $\text{Prg}'$  by adding or removing **unique** annotations does not adhere to the PEV.

**THEOREM 7.2 (MAXIMAL SET OF UNIQUE ANNOTATIONS ENFORCING THE PEV).** *For all programs  $\text{Prg}$  adhering to the PEV: (i) for all VM  $m$  of  $\text{Prg}$ ,  $\text{UNIQUE}(\text{Prg}, m) \subseteq \text{MaxUNIQUE}(\text{Prg}, m)$ ; (ii) the program  $\text{Prg}'$  obtained by adding **unique** annotations to  $\text{Prg}$  until, for all VM  $m$ ,  $\text{UNIQUE}(\text{Prg}', m) = \text{MaxUNIQUE}(\text{Prg}', m)$ , adheres to PEV.*

**PROOF.** By Def. 7.1  $F_m$  is a set-theoretic inclusion-preserving map and the powerset  $2^{S_m}$  is a complete lattice. By the Knaster-Tarski theorem [31] there exist smallest and greatest fixpoints of  $F_m$ . Moreover, the PEV (Def. 5.3.(2)) requires that  $\text{UNIQUE}(\text{Prg}, m)$  is a fixpoint of  $F_m$ . Now item (i) holds, because  $\text{MaxUNIQUE}(\text{Prg}, m)$  is the greatest fixpoint of  $F_m$ —the proof is as follows: let  $G$  be the greatest fixpoint of  $F_m$ ; clearly  $G \subseteq S_m$  and (since  $F_m$  is non-increasing monotone)  $G = F_m^n(G) \subseteq F_m^n(S_m)$  for all  $n \in \mathbb{N}$ ; but  $\text{MaxUNIQUE}(\text{Prg}, m)$  is the fixpoint obtained by iterating  $F_m$  on  $S_m$ . Item (ii) holds, because  $\text{Prg}'$  satisfies Def. 5.3—in particular: item (1) holds by definition of  $S_m$  and non-increasing monotonicity of  $F_m$ ; item (2) is satisfied by any fixpoint of  $F_m$ ; since  $\text{Prg}$  satisfies item (3), so does  $\text{Prg}'$ .  $\square$

*Definition 7.3 (Soundness of Delta-application).* Let  $m$  be a VM of  $\text{Prg}$ . Then  $m$  is *delta-application sound* in  $\text{Prg}$ , if for all  $xc \in \{\perp\} \cup \{\pi \mid \pi \text{ is a product of } m\}$  there exists a VM  $\text{Core Md1c}$  and a set  $D$  such that  $m \xrightarrow{\text{Prg}, xc} D, \text{Md1c}$  holds.  $\text{Prg}$  is *delta-application sound*, if all VMs  $m$  in  $\text{Prg}$  are delta-application sound.

Recall that programs are considered equal modulo permutation of class/interface definitions, field/method definitions, etc.

**THEOREM 7.4 (FLATTENING SOUNDNESS).** *If program  $\text{Prg}$  in normal form adheres to the PEV and is delta-application sound, then  $\varepsilon, \emptyset, \emptyset \xrightarrow{\text{Prg}^*} \text{Prg}' , A, \emptyset$  for some variability-free ABS program  $\text{Prg}'$ .*

**PROOF.** First we note that the rules in Def. 6.7 can be applied only a finite number of times, because the set of possible dependencies in  $\text{Prg}$  is finite (bounded by the set of variants per module). Thus termination is ensured.

The fact that  $\text{Prg}$  is in normal form guarantees: (i) all VM dependencies are defined in  $\text{Prg}$ ; (ii) all configuration expressions  $\text{ke}$  in syntactic dependencies are valid products of the corresponding VM. These two facts ensure that all dependencies in  $\text{Prg}$  correspond to an actual dependency  $(m, xc)$  where  $m$  is declared in  $\text{Prg}$  and  $xc$  is either  $\perp$  or a product of  $m$ . In particular, if we consider any rewriting sequence  $\varepsilon, \emptyset, \emptyset \xrightarrow{\text{Prg}^*} \text{Prg}' , A, D$ , all pairs  $(m, xc)$  in  $A, D$  are such that  $xc$  is either  $\perp$  or a product of  $m$ .  $\square$

## 8 IMPLEMENTATION AND EVALUATION

### 8.1 Integration into the ABS Tool Chain

We implemented the VM concept as part of the ABS compiler tool chain (with exception of open product definitions, currently under development). The implementation is available.<sup>3</sup> The readme in the repository describes how to access the case studies.

To integrate VMs into the ABS compiler tool chain, only the frontend (parser and preprocessor) needed to be changed. This is, because flattening (Sect. 6.2) produces variability-free ABS code, keeping ABS code generation and semantic analysis (type checking) as is. The ABS parser's grammar is extended with the constructs described in Sect. 4. As expected, ABS's existing delta application mechanism (including calls to `original(...)`) could be fully reused. The implementation also includes: (i) the normal form check (Def. 4.1), with error reporting in case it is violated (not yet fully implemented); (ii) the PEV check (Sect. 5) with error reporting in case PEV is violated; (iii) the flattening mechanism described in Sect. 6.2; (iv) adjustment of the feature model (needed, because VMs use a simpler feature modeling language than ABS's  $\mu TVL$  [6]).

### 8.2 Case Studies

ABS-VM was used in four case studies—the source code of the studies is available at the URL given above.

The first case study models from scratch a portal to compare insurance services [29]. It contains a product line model with three VMs in nearly 700 lines of code with eight features.<sup>4</sup> It uses VMs to model different insurance offers. Their interoperability is required so that users can compare them in the portal.

The remaining three case studies either refactor or extend existing ABS models using the VM concept. Each of them illustrates a different use of VMs to support interoperable variants:

**VMs vs. external tool chain.** The AISCO system uses an external ad-hoc mechanism in Java to mimic variable modules in ABS. In Sec. 8.2.1 we compare the original system with our reimplementation with VMs.

**VMs vs. exploiting traits.** The *FormbaR* model relied on specific patterns to handle interoperability through the class model and traits.<sup>5</sup> We show in Sec. 8.2.2 how the relevant parts of *FormbaR* are remodeled with VMs.

**VMs vs. standard ABS SPLs.** Using an ABS model of weak memory (Sec. 8.2.3), we show that without VMs, one would need to manually duplicate several modules.

**8.2.1 AISCO.** AISCO (Adaptive Information System for Charity Organizations) [40] is a modular web portal that supports the business processes (information, reporting, spending, expenditure) of charity organizations. It consists of an SPL implemented in ABS and its variability reflects the differing legal and operational requirements of the organizations. The code is in production at <https://aisco.splelive.id/>.

<sup>3</sup> <https://zenodo.org/record/5045008>

<sup>4</sup>The model contains four *further* features for the legacy SPL mechanism of ABS, kept for backwards compatibility.

<sup>5</sup>Traits [16, 34] are sets of methods that can be added to a class. The ABS-VM implementation supports traits. Since traits are orthogonal to the notion of VM we have not included them in the fragment of ABS-VM formalized in this paper. We refer to Damiani et al. [9] for a presentation of the notion of traits supported by ABS.

*Evaluation.* The requirements stipulate co-existence of multiple ABS variants, for example, different formats for financial reports. As this is not supported in current SPL approaches including ABS, an ad-hoc Java framework *on top of* ABS handled interoperability at runtime. For the case study, the main aspects of AISCO were re-implemented in ABS-VM in 160 lines of code, one VM with four features and five different deltas for financial reporting. All variants can interoperate within one and the same program generated from the ABS-VM code, instead of relying on an external, non-generic framework that is deeply intertwined with the ABS model.

**8.2.2 FormbaR.** This is a re-modeling of the industrial *FormbaR* case study [24] (the basis of Sect. 2). VMs are useful to model infrastructure elements, such as signals coming in different variants that must coexist and interoperate within the same infrastructure model. The *FormbaR* model uses one class per infrastructure element, but this relies on the fact that in this case classes are a sufficient unit for variability. The domain is modelled as a tree-like type structure – additional constraints are imposed only implicitly. The part of the model that involves interoperable variability has been re-implemented using VMs.

*Evaluation.* The partial refactoring showed that by introducing a VM with five features (*Main*, *Pre*, *Speed*, *Signal*, *Pov*) and seven deltas, the total number of lines for the five remodeled kinds of signal<sup>6</sup> is reduced from 241 to 180 (-25%). Excluding the lines of code needed only for variability modeling (configuration knowledge and delta headers), the remodeled part has 163 lines (-33%). The original model [24] uses traits to reduce code duplication in the implementation of the different kinds of signals. The ABS-VM reformulation of the model does not need to use traits. The reformulated model is: (i) shorter (in terms of length of code), because in the original model there is a separate class for each kind of signal; and (ii) more comprehensible: the feature model captures constraints in the model that were implicit before (for example, that two traits should not be used by the same class) and it declaratively connects code variability to the domain model.

**8.2.3 Weak Memory Models.** This case study is the VM extension of an ABS model of weak memory [23]. In sequentially consistent memory models all read- and write-accesses of some code are processed in the order they are issued. Weakly consistent (for short: weak) memory models allow partial or complete re-ordering of accesses to increase efficiency. The ABS weak memory model formalizes different relaxation strategies and device models, so as to allow to simulate and analyze their effects. A weak memory model in the case study is a class that manages a list of memory accesses. Variability includes different types of reordering (read before write, etc.). We extended the existing ABS model to two devices with two memory systems each: any of the four memory models can be different.

*Evaluation.* The ABS-VM model contains one module for memory models and one for devices (i.e., pairs of memory models). For comparison, we implemented this with product lines based on standard DOP. As we potentially need four different memory models, this required to copy the memory model module *including all deltas* four times. Furthermore, the device module had to be copied twice.

<sup>6</sup>*Main signals, presignals, speed limiters, pre-speed limiters and points of visibility* [24].



Essentially, we must perform *manually* part of the VM flattening until we can rely standard operations on the modules.

The ABS-VM version has 485 LoC, of which 440 LoC are the two variable modules. The standard ABS version has 1322 LoC (+272%), of which 620 LoC are concerned with deltas and variability and 582 are the core product of the modules for memory models and devices. We refrained from reducing code duplication through traits to illustrate that product line systems without native support of interoperable variants can only replicate this behavior through massive code duplication.

If a module has  $p$  products, then in ABS-VM only  $p$  configurations are declared, for *any* number of used variants. Another observation is that to connect  $n$  variants, one needs to declare  $p^n$  products: one for each combination. Hence, in addition to the additional delta declarations, this blows up the feature model unreasonably.

## 9 RELATED WORK

*On Programming Constructs for MPLs and Variant Interoperability.* Schröter et al. [36] advocate the use of suitable interfaces to support compositional analysis of MPLs, consisting of *feature-oriented programming* (FOP)<sup>7</sup> SPLs of Java programs, during different stages of the development process. Damiani et al. [14] informally outlined an extension of DOP to implement MPLs of Java programs by proposing linguistic constructs for defining an MPL as an SPL that imports other SPLs. In their proposal the feature model and artifact base of the importing SPL is entwined with the feature models and artifact bases of the imported SPLs. Therefore, in contrast to VMs, the proposal does not support encapsulation at SPL level. More recently, Damiani et al. [12, 13] formalized an extension of DOP to implement MPLs in terms of a core calculus, where products are written in an imperative version of Featherweight Java [19, 20]. The idea was to lift to the SPL level the use of dependent feature models to capture MPLs, as advocated by Schröter et al. [35, 37]. Like the earlier paper [14], the proposed SPL construct [13] models dependencies among different SPLs at the feature model level: to use two (or more) SPLs together, one must compose their feature models. In contrast, VMs do not require feature model composition.

The proposals mentioned above do not support variant interoperability [11]. Setyautami et al. [38] addressed variant interoperability at the level of static UML class diagrams. In this paper we consider executable Java-like code.

Variant interoperability in terms of ABS code is addressed in our previous work [11], where we considered a set of product lines, each *comprising* a set of modules. However, in that proposal, encapsulation is not realized by mechanisms at the module level (as in VMs): unique declarations are supported (unsatisfactorily) by common modules (which is not fine-grained enough), and the concepts of modularity (through modules) and variability (through product lines) are intertwined. In contrast, the VM concept proposed in this paper unifies modules and product lines by *adding* the capability to model variability directly to modules: each module is a product line, each product line is a module. This drastically simplifies the language, yet allows more far-reaching reuse of the DOP

<sup>7</sup>FOP [1, Sect. 6.1], [3], [25] can be characterized as the restriction of DOP, where there is a one-to-one mapping between deltas and features (each delta is activated if and only if the corresponding feature is selected), the application order is total, and there are no class/interface/field/method removal operations [33].

mechanism natively supported by ABS. Furthermore, VMs ease the cognitive burden of variability modeling, extending a common module framework, instead of adding another layer on top.

*On Variability-aware Module Systems.* Kästner et al. [26] propose a *variability-aware module system* (that we call VAMS in the following) for procedural languages. Like in our proposal, each VAMS module is an SPL. However, there are four important conceptual differences, which we outline in the following:

(i) VAMS does not encapsulate variability (cf. Sect. 5). Namely, modules import function declarations without specifying the modules from which they should be imported. In order to generate a variant, VAMS requires the user to write a composition expression, which lists all the modules to be composed and resolves dependencies and ambiguities (e.g., when a module imports a function that is defined in two different modules) by specifying how functions are renamed or hidden (and how features are renamed, selected or deselected). So, VAMS is not concerned with explicit dependencies between modules, which are crucial to usability and central to the PEV introduced in this work. By exploiting PEV, VMs achieve simplicity and usability: configuring a single VM  $\mathbb{M}$  triggers automatic generation of all required variants of  $\mathbb{M}$  and other VMs.

(ii) The design of VAMS does not target variant interoperability (Kästner et al. [26] do not mention this issue). Making two variants of the same module to co-exist, requires to create copy of the module and to rename (possibly by exploiting the module composition language provided by VAMS) all its features and all its exported functions. Instead, providing usable support to variant interoperability is a central design goal of VM.

(iii) VAMS variability is achieved explicitly by using an annotative approach: code elements (import/export declarations and function declarations) are annotated with presence conditions (propositional formulas over features). In VM variability is achieved explicitly by DOP for class/interface declarations and implicitly for export/import declarations.

(iv) VAMS is formalized by building on a calculus in the spirit of Cardelli's module system formalization [5] for procedural programming languages, where a module consists of a set of imported typed function declarations and a list of typed function definitions, and is implemented as a module system for C code. Therefore, VAMS is tailored for procedural language, where the interface of each module describes names and types of imported and exported functions, and there is a global function namespace. Moreover, even though each module has its own feature model, there is a global feature namespace. In contrast, VMs target Java-like languages, are based on the module system of ABS [17, 21] (a fairly standard module system close to Java and Haskell) and are implemented as an extension of the ABS module system. Each VM has a local namespace (which reduces overhead), also features are local to VMs.

*On Variability Modules in Java.* The paper [39] suggests that VM can be implemented on top of any Java-like language with modest effort. The solution<sup>8</sup> presented there takes a different approach from the present account: it dispenses with explicit language constructs to model variability, but uses only standard Java constructs. This is

<sup>8</sup>The VM concept presented in [39] is based on the research reported here, but was published earlier due to the uncertainties inherent to peer-reviewed publication.

achieved with an architectural pattern: delta application is achieved with decorators, the name space is managed with abstract factories, and each product is a module declaration in itself. The sole reliance on standard Java constructs comes with some limitations: unique class/interface declarations are not directly supported (but can be achieved by suitable **final** annotations). In consequence, the PEV is not enforced. Open product declarations are not supported. Unsoundness of a product might only be detected at runtime, because reflection is used for module name resolution instead of flattening. Therefore, [39] does not feature a formal semantics of VM and family-based checking.

## 10 CONCLUSION AND FUTURE WORK

This work presents variability modules, a novel approach to implement MPLs consisting of DOP SPLs of Java-like programs, where different, possibly interdependent, variants of the same SPL can coexist and interoperate. The PEV allows to encapsulate variability mechanisms by standard modules.

We are currently extending the implementation (cf. Sect. 8.1) to support: (i) open product definitions; and (ii) a family-based analysis [15, 42, 43] that, given an ABS-VM program  $\text{Prg}$ , checks—without actually generating any variant—whether all variants of the VMs in  $\text{Prg}$  can be generated and, as a whole, form a well-typed variability-free ABS program (implying that  $\text{Prg}$  can be flattened and is well-typed).

In future work we would like to validate the extended tool chain by further developing the use cases (cf. Sect. 8.2) and by considering novel use cases.

## A DELTA APPLICATION RULES

In this appendix we present the rules describing the application of an ordered sequence of deltas  $\overline{\text{Dlt}}$  to a sequence of interface/class definitions  $\overline{\text{Defn}}$  (see Definition 6.4).

The rules, given in Fig. 7, fall into the following categories:

**Rules for a Sequence of Deltas** describe how to apply each of the deltas in a sequence. D:EMPTY removes the delta if no operations are left to execute. Rules D:INTER and D:CLASS extracts the first interface/class operation from the delta and applies it to the list of definition. D:END concludes the application process when the sequence of the deltas to be applied is empty.

**Rules for a Delta** describe how to apply the actions specified by a delta to a whole class or interface definition. Rule D:ADDSI adds an interface by adding its definition to the list of definitions. Rule D:REMSI removes an interface by looking up its definition using the name from the delta modifier. The rules for classes, D:ADDS C and D:REMS C are analogous. Rules D:MOD I and D:MOD C modify an interface, or class, by applying the rules for interface modifiers (or class modifiers).

**Rules for Extends/Implements Clauses** modify the *extends* clauses of interfaces and *implements* clauses of classes. by removing (D:EM:REMS) or adding (D:EM:ADDS) it. Rule D:EM:EMPTY is applied if all modification of the clause have been applied.

**Rules for Interfaces** modify interfaces. Rule D:I:EMPTY is applicable when no further modification is requested on the given interface, so that the result is the interface itself. Rule D:I:ADDS adds the specified method header to the interface (provided that no header with

this name is already present in the interface). Rule D:I:REMS removes an existing method header from the interface.

**Rules for Classes** modify classes. They are very similar to the ones for interfaces, with two exceptions: first, manipulation of method headers is replaced by manipulation of fields (rules D:C:ADDS F and D:C:REMS F) and methods implementations (rules D:C:ADDS M and D:C:REMS M). Second, methods may be modified using rule D:C:MODS. This rule replace the method implementation, but keeps the old implementation with a fresh name. If the new implementation contains an *original* statement, then this statement is replaced by a call to the old implementation.

### Rules for a Sequence of Deltas

$$\begin{array}{c} \text{D:EMPTY} \\ \hline (\text{delta } D; \overline{\text{Dlt}}, \overline{\text{Defn}}) \rightarrow (\overline{\text{Dlt}}, \overline{\text{Defn}}) \\ \\ \text{D:CLASS} \\ \hline (\text{delta } D; \text{CO } \overline{\text{CO}} \overline{\text{IO}} \overline{\text{Dlt}}, \overline{\text{Defn}}) \rightarrow (\text{delta } D; \overline{\text{CO}} \overline{\text{IO}} \overline{\text{Dlt}}, ((D; \text{CO}) \bullet \overline{\text{Defn}})) \\ \\ \text{D:INTER} \\ \hline (\text{delta } D; \text{IO } \overline{\text{IO}} \overline{\text{Dlt}}, \overline{\text{Defn}}) \rightarrow (\text{delta } D; \overline{\text{IO}} \overline{\text{Dlt}}, (D; \text{IO}) \bullet \overline{\text{Defn}}) \\ \\ \text{D:END} \\ \hline (\varepsilon, \overline{\text{Defn}}) \rightarrow \overline{\text{Defn}} \end{array}$$

### Rules for a Delta

$$\begin{array}{c} \text{D:ADDSI} \\ \hline \frac{\text{nameOf}(\text{ID}) \notin \text{nameOf}(\overline{\text{Defn}})}{(D; \text{adds ID}) \bullet \overline{\text{Defn}} \rightarrow \text{ID } \overline{\text{Defn}}} \quad \text{D:REMSI} \\ \hline \frac{\text{nameOf}(\text{ID}) = \text{I}}{(D; \text{removes I}) \bullet (\text{ID } \overline{\text{Defn}}) \rightarrow \overline{\text{Defn}}} \\ \\ \text{D:MODSI} \\ \hline (D; \text{modifies interface I EM } \{ \overline{\text{SO}} \}) \bullet (\text{interface I extends } \overline{\text{IR}} \{ \overline{\text{MH}} \} \overline{\text{Defn}}) \\ \rightarrow (\text{interface I extends } (\text{EM} \bullet \overline{\text{IR}}) \{ \overline{\text{SO}} \bullet \overline{\text{MH}} \} \overline{\text{Defn}}) \\ \\ \text{D:ADDS C} \\ \hline \frac{\text{nameOf}(\text{CD}) \notin \text{nameOf}(\overline{\text{Defn}})}{(D; \text{adds CD}) \bullet \overline{\text{Defn}} \rightarrow \text{CD } \overline{\text{Defn}}} \quad \text{D:REMS C} \\ \hline \frac{\text{nameOf}(\text{CD}) = \text{C}}{(D; \text{removes C}) \bullet (\text{CD } \overline{\text{Defn}}) \rightarrow \overline{\text{Defn}}} \\ \\ \text{D:MODSC} \\ \hline (D; \text{modifies class C EM } \{ \overline{\text{AO}} \}) \bullet (\text{class C implements } \overline{\text{IR}} \{ \overline{\text{FD}} \overline{\text{MD}} \} \overline{\text{Defn}}) \\ \rightarrow (\text{class C implements } (\text{EM} \bullet \overline{\text{IR}}) \{ (\overline{\text{D}}; \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}}) \} \overline{\text{Defn}}) \end{array}$$

### Rules for Extends/Implements Clauses

$$\begin{array}{c} \text{D:EM:EMPTY} \quad \text{D:EM:ADDS} \\ \hline \varepsilon \bullet \overline{\text{IR}} \rightarrow \overline{\text{IR}} \quad (\text{adds } \overline{\text{IR}} \text{ EM}) \bullet \overline{\text{IR}} \rightarrow \text{EM} \bullet (\overline{\text{IR}} \overline{\text{IR}}) \\ \\ \text{D:EM:REMS} \\ \hline (\text{removes } \overline{\text{IR}} \text{ EM}) \bullet (\overline{\text{IR}} \overline{\text{IR}}) \rightarrow \text{EM} \bullet \overline{\text{IR}} \end{array}$$

### Rules for Interfaces

$$\begin{array}{c} \text{D:I:EMPTY} \quad \text{D:I:ADDS} \\ \hline \varepsilon \bullet \overline{\text{MH}} \rightarrow \overline{\text{MH}} \quad \frac{\text{nameOf}(\overline{\text{MH}}) \notin \text{nameOf}(\overline{\text{MH}})}{(\text{adds } \overline{\text{MH}} \overline{\text{SO}}) \bullet \overline{\text{MH}} \rightarrow \overline{\text{SO}} \bullet (\overline{\text{MH}} \overline{\text{MH}})} \\ \\ \text{D:I:REMS} \\ \hline (\text{removes } \overline{\text{MH}} \overline{\text{SO}}) \bullet (\overline{\text{MH}} \overline{\text{MH}}) \rightarrow \overline{\text{SO}} \bullet \overline{\text{MH}} \end{array}$$

### Rules for Classes

$$\begin{array}{c} \text{D:C:EMPTY} \quad \text{D:C:ADDS F} \\ \hline \varepsilon \bullet (\overline{\text{FD}} \overline{\text{MD}}) \rightarrow \overline{\text{FD}} \overline{\text{MD}} \quad \frac{\text{nameOf}(\overline{\text{FD}}) \notin \text{nameOf}(\overline{\text{FD}})}{(D; \text{adds } \overline{\text{FD}} \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}}) \rightarrow (D; \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}})} \\ \\ \text{D:C:ADDS M} \\ \hline \frac{\text{nameOf}(\overline{\text{MD}}) \notin \text{nameOf}(\overline{\text{MD}})}{(D; \text{adds } \overline{\text{MD}} \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}}) \rightarrow (D; \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}} \overline{\text{MD}})} \\ \\ \text{D:C:REMS F} \\ \hline (\text{removes } \overline{\text{FD}} \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}}) \rightarrow (D; \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}}) \\ \\ \text{D:C:REMS M} \\ \hline (D; \text{removes } \overline{\text{MH}} \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MH}} \{ \overline{\text{S}} \text{return E;} \} \overline{\text{MD}}) \rightarrow (D; \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MD}}) \\ \\ \text{D:C:MODS} \\ \hline \frac{\text{nameOf}(\overline{\text{MH}}) = \text{nameOf}(\overline{\text{MH}'}) = m \quad \overline{\text{S}'} = \overline{\text{S}}[D_{-}m / \text{original}]}{\text{E}' = \text{E}[D_{-}m / \text{original}] \quad \overline{\text{MH}'} = \overline{\text{MH}}[D_{-}m / m]} \\ (D; \text{modifies } \overline{\text{MH}} \{ \overline{\text{S}} \text{return E;} \} \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MH}} \{ \overline{\text{S}'} \text{return E}'; \} \overline{\text{MD}}) \\ \rightarrow (D; \overline{\text{AO}}) \bullet (\overline{\text{FD}} \overline{\text{MH}} \{ \overline{\text{S}'} \text{return E}'; \} \overline{\text{MH}'} \{ \overline{\text{S}'} \text{return E}'; \} \overline{\text{MD}}) \end{array}$$

Figure 7: Delta Application Rules

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