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An Integrated Model-based Tool Chain for Managing Variability in Complex System Design

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Abstract—Software-intensive systems in the automotive domain are often built in different variants, notably in order to support different market segments and legislation regions. Model-based concepts are frequently applied to manage complexity in such variable systems. However, the considered approaches are often focused on single-product development. In order to support variable products in a model-based systems engineering environment, we describe a tool-supported approach that allows us to annotate SysML models with variability data. Such variability information is exchanged between the system modeling tool and variability management tools through the Variability Exchange Language. The contribution of the paper includes the introduction of the model-based product line engineering tool chain and its application on a practical case study at Volvo Construction Equipment. Initial results suggest an improved efficiency in developing such a variable system.

Index Terms—Product Line Engineering, Model-based Systems Engineering, Integrated Tool Chain

I. INTRODUCTION

Product Line Engineering (PLE) [1] is commonly used in the automotive industry [2]. This approach allows to combine the economic benefits of mass production with customization for specific purposes or market segments. PLE is a relatively modern approach for the design and production of software-intensive systems sharing a common platform or code base but dedicated to different systems - variants. Product variants are obtained by configuring and enabling various common and variable features in the product line. The approach has the potential to bring up to ten-fold productivity gains as shown in an extended survey [3].

In literature, the majority of PLE studies consider software-only systems [4]. Complex systems, however, might include several domains, e.g., hardware and software. Model-based systems engineering (MBSE), [5], is often applied for the development of such systems, e.g. [6]. In addition to the implementation of software, MBSE includes activities such as requirement engineering, system architecture specification, verification and validation, etc. In the MBSE world, the model is a first-class citizen of the engineering process. Therefore,

we want to make it possible to manage variability in different engineering process phases, e.g., requirement engineering, system design, verification and validation, in addition to the variability in implementation. As models, in an MBSE environment, usually prescribe and coordinate development across different engineering domains, it is important to manage variability in the complete MBSE process.

Systems Modeling Language (SysML) [7] is a widely used modeling language in industrial practice [8]. In this paper, we propose an approach to deal with SysML models in a PLE-based approach. We make it possible to add variability information from variability management tools into SysML models and generate individual system variants based on the variability information. The information between the variability management tool and system modeling tool is exchanged through the Variability Exchange Language (VEL) [9].

We instantiate the approach in practice using an integrated tool chain based on tools from the MegaM@Rt2 [10] and REVaMP2 [11] projects.

The rest of the paper is structured as follows. Section II introduces the context in which Volvo Construction Equipment (Volvo CE) develops highly variable diesel engine systems and the motivation for migrating towards an MBSE-PLE approach. Section III provides a general overview of our proposed approach. The tool chain and its application to the Volvo CE example are described in Section IV. Preliminary results of the initial application suggest that PLE concepts in an MBSE environment have the potential to improve efficiency in the development of complex and variable systems. After the discussion from Section V, we briefly dive into the related work in Section VI. Finally, Section VII summarizes the paper.

II. MOTIVATING EXAMPLE

Volvo CE develops and manufactures off-road construction machinery such as articulated haulers, excavators, wheel loaders, as shown in Figure 1. All construction machinery share a common engine platform. The common platform is outsourced to a technology provider within the Volvo Group. The Engine



Fig. 1. Volvo CE Machinery

Department of Volvo CE then extends the platform for Volvo CE specific applications. The required engine behavior and performance are vastly different between applications. For example, in the articulated hauler, the engine is connected to a transmission, while in an excavator, the engine is connected to a hydraulic pump. In addition to the variable requirements from product platforms (e.g. excavators, haulers), the engine system must fulfill legal requirements for exhaust emissions and diagnostic services in different legislation regions (US, EU, China, and non-regulated markets).

The technology provider develops both the base engine hardware (a bare-bones engine system) and engine control software. To adapt the base engine for Volvo CE specific applications, auxiliary components, such as sensors, oil filters, turbochargers, and cooling fans, are developed at the Engine Department and added to the base engine. Consequently, the software configuration parameters are adjusted to enable or disable software features that control the installed auxiliary components. The software then needs to be calibrated to meet engine performance requirements (e.g. max engine power and torque response) at the Engine Controls Department at Volvo CE. In order to cope with the increasing complexity of both the base engine platform and the auxiliary components, the Engine Department of Volvo CE is in the process of adopting an MBSE approach based on SysML. The aim is to bring together the two different engineering domains: hardware (physical engine and auxiliary components) and software (engine controls software). However, one of the major factors that have to be considered during systems engineering at the Engine Controls department is the fact that engine systems must support a large number of variants. At the moment, SysML does not provide a means to document variability within models.

As the models at the Engine Controls department include requirements, system structure and behavior, the system modeling approach must support variability on all SysML diagram types. Moreover, the approach must allow one to trace a feature at different abstraction levels, e.g. from requirements to behavior specifications to individual software parameters.

III. SOLUTION

In order to address the needs of organizations that are developing variable products, such as the described Volvo CE example, we present an approach that combines PLE and model-based development in a common process. Figure 2 illustrates the proposed approach. The left side in the figure depicts the *problem domain* where the variability in the system, the relations and the constraints between variable features are

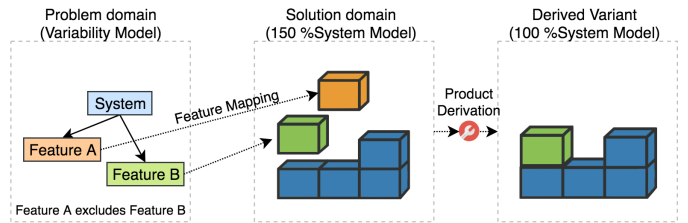


Fig. 2. A generic approach for combining variability modeling with system modeling

described. In our approach, we propose the use of *feature models*, which are both documented extensively in literature ([12], [13]) and applied in industrial practice [3].

Once the system variability is described in the variability model, the variability must also be implemented in the solution domain. The middle part of Figure 2 depicts the *solution domain*. This is where the system models of both common and variable features are developed.

To document variability in models we use *150% models* ([14], [15], [16]) i.e. all system variants are modeled within a single over-specified model. The 150% approach to product lines has the potential to increase product quality, reduce amount of artifacts that need to be maintained, reduce lead-time, etc. [17]. The *150% model* contains all system variations within a single model. It is important to consistently exchange variability information between the problem and solution domain. In our proposed tool chain, we use the Variability Exchange Language to integrate the design and variability management tools (cf. Section IV).

Variability models serve as a starting point for customers during the definition of a product variant. Customers select variable product features based on their needs. Constraints and relations between features restrict how features can be combined. The variability information then needs to be exchanged with the system modeling tool that contains the *150% model*. The system modeling tool should then be able to generate a *100% system model* of a single system variant. As illustrated in the right part of Figure 2, the derived model should include only model artifacts from the solution domain that were selected during feature selection. For example, these can be requirement models, system architecture, verification procedures, etc.

Since different organizations may have different systems engineering processes and use models at different levels of the process, we strive that our approach is generic enough to be applicable to any phase of their systems engineering process by making it possible to model variability on any diagram type, e.g. requirement models, structure, behavior, etc.

IV. TOOL CHAIN

This section describes a tool chain that supports the approach discussed in the previous section.

In the tool chain, we use the `pure::variants` tool from pure-systems [18] to manage variability in the problem domain and the Modelio [19] modeling tool to model the

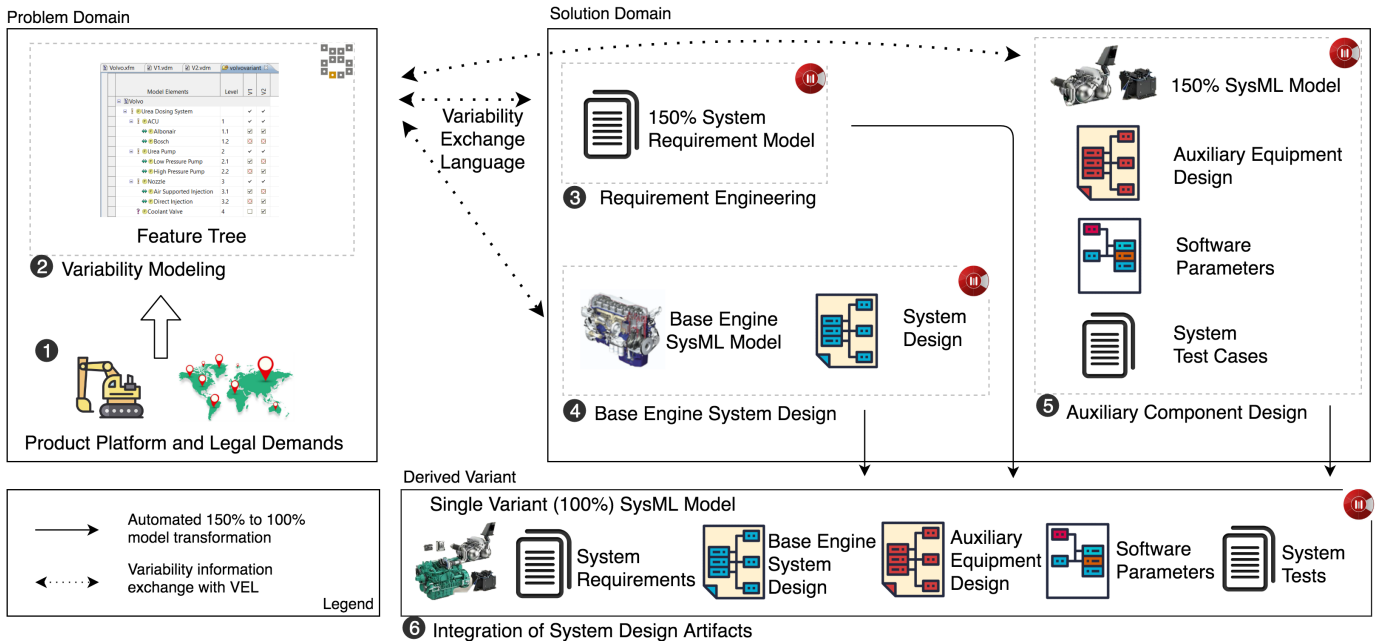


Fig. 3. Product Line Engineering Process with the Model-based Tool Chain

system in the solution domain. In order to integrate the two tools, the Variability Exchange Language was used. It allows us to exchange variability information between the problem and solution domain. `pure::variants`, as a variability management tool, already supported VEL. However, Modelio had to be extended with mechanisms to support modeling of variability in system models and to exchange information via VEL.

In Figure 3, we illustrate the proposed tool chain workflow in more detail in the context of a Volvo CE use case. It covers several phases of an engine development process starting with requirements and continuing with system design and verification, to some extent.

In Step ①, customers (product platforms) define their requirements on the system, e.g. needed torque, power, engine start/stop function, etc. In addition, depending on the legislation region in which the customer plans to use the engine, the exhaust emission and diagnostic requirements are varying.

In Step ②, based on their requirements, customers select system features from the feature model with the `pure::variants` tool, as illustrated in Figure 4.

`pure::variants` is a variability management tool supporting VEL to facilitate product line development. As depicted in Figure 4, a feature model is specified to document all variability of the product line. A set of system features and the possible variants of the feature are shown. The example shows the variability of the Urea Dosing System (UDS) which is a subsystem of the engine. A single UDS consists of a Diesel Exhaust Fluid (DEF)¹ storage tank, a pump that pressurizes the DEF and and injection nozzle through which

¹DEF is a mixture of urea and water that chemically reacts with exhaust gases to reduce harmful emissions.

the DEF is dispersed into the exhaust stream. There are also a DEF quality sensor and a valve that controls engine coolant circulation throughout the system in order to defrost it at low temperatures. An actuator control unit (ACU) is used to control the pump in the system.

The constraints between features are defined manually by system engineers during the system design. The variability management tool only defines and manages the system feature model without any other knowledge about how the features are implemented. The feature model and feature constraints

| Model Elements | | Level | ✓ | ✗ |
|-------------------------|----------------------------------|-------|---|---|
| Volvo | Urea Dosing System System | | ✓ | ✓ |
| ACU | Feature | 1 | ✓ | ✓ |
| Albonair | Variant A | 1.1 | ✓ | ✓ |
| Bosch | Variant B | 1.2 | ✗ | ✗ |
| Urea Pump | | 2 | ✓ | ✓ |
| Low Pressure Pump | | 2.1 | ✓ | ✗ |
| High Pressure Pump | | 2.2 | ✗ | ✓ |
| Nozzle | | 3 | ✓ | ✓ |
| Air Supported Injection | | 3.1 | ✓ | ✗ |
| Direct Injection | | 3.2 | ✗ | ✓ |
| Coolant Valve | | 4 | □ | ✓ |

Fig. 4. Feature Model example

restrict the variability space of the system, reducing the risk of creating a variant with incompatible features. Some users might have requirements that are outside the scope of the current product family, i.e. a feature not present in the current set of features. In such a situation there are two possibilities: (i) extend the product line to include the new feature or (ii) implement the new requirement only for the individual variant. Both possibilities will be discussed later in this section. Once

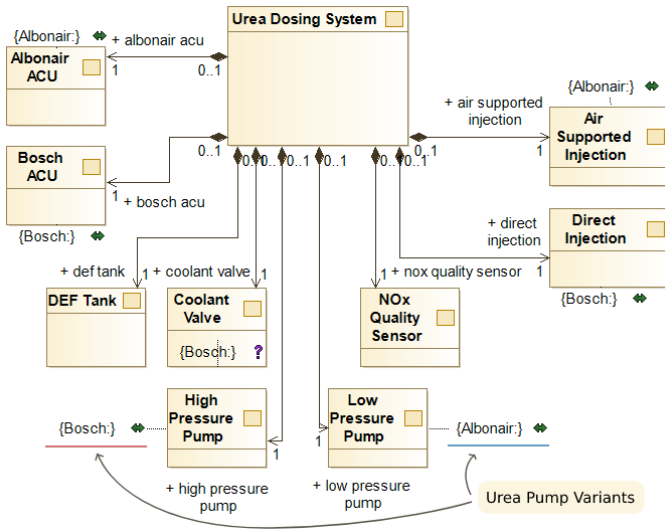


Fig. 5. Annotated SysML model

the feature selection is finished, the variability information from `pure::variants` (Step ②) is exchanged with Modelio through the VEL.

Modelio is an extensible UML/BPMN/SysML modeling tool. A module has been developed to extend the tool and allow variability information annotation on top of any kind of supported modeling language (e.g. UML/SysML in our context). As shown in Figure 5, a SysML Block Definition Diagram (BDD) of the UDS is annotated with variability information. It is a desensitized diagram that includes two variants of the UDS. The blocks of the two variants are annotated as 'Bosch' and 'Albonair' in Figure 5.

In order to exchange information between Modelio and `pure::variants`, Modelio first generates a serialized XML file in the VEL, as depicted in Figure 6. The XML file contains information of the *150% model*. For simplicity purposes, we show one variation point, named 'Physical Architecture', with two possible variants, named 'Albonair' and 'Bosch', together with information of model elements that belong to either feature. The VEL file is then read by `pure::variants` and mapped to the feature diagram shown in Figure 4. Mapping is done through a naming convention based on the prototype implementation of the variability modeling functionality in Modelio. The features that the user did not select in Step ② are then removed from the VEL file in `pure::variants` and a *new VEL file* is then generated.

This new file contains information with the feature set of a single variant, i.e., a *100% file*. Modelio uses the new VEL file as an input for a model transformation where elements not contained in the VEL file of a single variant are removed from the *150% system model*. As an example, in ③ all product family requirements are contained. Modelio, performs a model transformation based on the VEL file exchange to generate a *100% requirement model* that is stored separately into ⑥.

The requirements define the performance and driveability

goals of the base engine system and auxiliary components. For example, the duration of the engine warm-up function when operating in cold conditions.

The base engine software features and interfaces are configured in ④. As all engine variants are built on a single engine platform, it is necessary to enable or disable software functions and system interfaces based on the application. The configuration is performed by enabling or disabling software parameters. The derivation of software configuration parameters is again automated based on the same feature selection from ② and the single variant model elements are again stored into the new model repository, ⑥.

Finally, in ⑤ it is necessary to select appropriate engine auxiliary components (sensors, oil tanks, hoses, radiators, etc.) and configure software functions that control these. Again, based on the feature selection from ②, the annotated *150% model* (containing the all auxiliary component design, software parameters, and tests) is transformed to remove all features that were not selected and generate a *100% model* containing only the selected elements.

The variations in requirements, base engine, and auxiliary components are resolved and an individual model is generated and stored in a new model repository in ⑥. This final system model then drives the engine assembly and activities such as performance calibration.

Now looking back at the case when customer requirements can not be mapped to any feature in the product line. The first possibility is to extend the product line and implement the required feature. That is, the feature model in ② must be extended to include the new feature. Then, the requirements in ③ and system design in ④ and ⑤ must be extended to implement the new feature. The process from selecting variants in the feature model to product derivation needs to be performed again to derive the new variant. The second possibility is to select the closest possible variant in ②, then once a product based on the feature selection is derived in ⑥, it is modified to implement the new requirements. The first approach develops the new feature to be reusable in new projects in the future, while the second approach develops the feature for only one variant.

V. DISCUSSION

We first discuss the approach based on the quality criteria for product lines as defined in [20].

Pre-planning effort. Implementing product lines always requires some pre-planning, at least to define the scope of the product line. System models are often created iteratively and as it is with annotative approaches in general ([20]), our *approach enables the product line to be annotated as system models are evolving with little pre-planning*. However, it is important to consider that no or little pre-planning might require significant effort to implement new features in later stages, as it might require large parts of the product to change.

Feature traceability evaluates support for mapping of features between the feature model and implementation models. The use of VEL for exchange of variability information allows

```

<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<variability-exchange-models id="root">
  <version>0</version>
  <capability>...</capability>
  <variability-exchange-model type="variationpoint-description" id="Physical Architecture">
    <xor-structural-variationpoint id=ACU">
      <variation id="Albonair">
        <corresponding-variable-artifact-element>
          <uid>de74b43c-4c43-4506-9c61-a210d79cdfef1</uid>
          <uid>c9551405-09f1-4274-a822-3d95f6d44f3f</uid>
          <uid>29e2baef-4d0a-40fd-9bbb-f65331c4d3f6</uid>
        </corresponding-variable-artifact-element>
        <condition type="single-feature-condition">Albonair</condition>
      </variation>
      <variation id="Bosch">
        <corresponding-variable-artifact-element>
          <uid>455e2c8c-391e-4f84-84fa-35e2883b41a6</uid>
          <uid>31efc977-05c5-4f4f-8179-1c6dd78f0ba2</uid>
          <uid>c7601d85-733a-463b-a1f1-f85ab3d4d170</uid>
          <uid>aace2ef1-3ef0-48a6-82fa-df57f8075d13</uid>
        </corresponding-variable-artifact-element>
        <condition type="single-feature-condition">Bosch</condition>
      </variation>
    </xor-structural-variationpoint>
  </variability-exchange-model>
</variability-exchange-models>

```

Fig. 6. Generated VEL

us to trace the features from the feature model directly to system model elements. VEL also allows us to trace a feature to multiple SysML models and model elements. *That is, a feature can be mapped to any number of model elements that implement the given feature.*

Separation of concerns, i.e. capability of the tool chain to support a separation between variable aspects of system features. Traditionally, in model-based development, views and viewpoints are used to express different concerns of the system design [21]. A view is a representation of the system from a perspective (viewpoint) of a stakeholder of a related concern. With SysML, a view can be considered as a set of model diagrams that allow the users to visualize, analyze and reason about a specific system concern or feature [22]. Separation of concerns mainly depends on the implementation of the system, i.e. whether the system is organized into cohesive components. Cross-cutting concerns, for example, the diagnostic function of the engine, however, span across multiple system components. In such cases, *annotating model elements with variability information explicitly exposes the cross-cutting features.*

Information hiding, i.e. separation of a component into its internal logic and external interfaces is inherently supported in SysML. Since our tool chain supports annotation on any model element, *encapsulated model elements of any feature can be annotated with variability, thus enabling information hiding with regards to features.*

Granularity, i.e. the level of detail at which variability can be implemented in system models. Our proposed annotative approach provides fine-grained granularity. That is, *it allows annotation on all model element types and properties of such elements, as well as annotation on the relationship links between elements.*

Uniformity states that variability in all product line artifacts should be encoded consistently. *Our tool chain provides good uniformity as all product artifacts are SysML model elements and are annotated in the same fashion.*

Based on the initial application, it was noted that the feature model and the constraints between features improve the consistency of system variants as the constraints restrict the possibility to create an invalid variant. The requirement elicitation time from customers (product platforms in the Volvo CE case) can be reduced since customers do not need to interact with domain experts to define a system variant except in the situation when customer requirements can not be mapped to any feature. This situation was described in Section IV. The feature model also received positive feedback from managers and non-technical stakeholders as it allowed them to understand the implications of certain system variants without needing extensive technical knowledge of the system or the domain.

VI. RELATED WORK

MBSE with SysML has been widely used in the industry in various domains, for example, aerospace [6] and automotive [23]. SysML can be extended with profiles and stereotypes to support variability [24]. This approach does not require a separate variability management tool. However, compared to our approach, it does not support the modeling of variability in SysML behavior diagrams, which are an important part of the system design. Another approach for modeling variability with SysML is presented in [25]. But again, it is not clear how variability is captured in behavior models. As stated in an literature survey, [8], activity and state machine diagrams are widely used in systems engineering. Thus, it is important to be able to define variants in behavior models as well.

The `pure::variants` tool was applied in a number of studies and industrial examples such as: [17] [26]. The later being interesting to us as it uses VEL to add variability information on software code. Combining our approaches would allow to have feature traceability through the complete development cycle of a system, from requirements to the system design and then the actual system implementation.

Another use of the same variability management tool and VEL is reported in the experience report in [27]. It describes a methodical and tooling approach with similar concepts to ours. However, their approach uses a custom-built tool to support variability in the problem domain throughout the complete application lifecycle.

Feature modeling, of course, is not the only approach and many of them are compared in [28]. For example, model views can also be used to handle variability in a modeling context [29]. Another study suggests Orthogonal Variability Modeling for variability management in SysML models [30]. Nevertheless, feature-modeling seems to be the most popular one based on a survey with industrial practitioners [3].

VII. CONCLUSION

MBSE is a common approach in practice for the development of complex, software-intensive systems. However, as presented in the Volvo CE example, organizations face challenges where many similar products must be developed and maintained for different customers. To deal with the highly variable systems, PLE is often applied. To combine the benefits of both worlds, PLE and MBSE, we have presented an approach that allows us to integrate variability information into design models of complex systems. The approach is supported by our tool chain for which we extend the Modelio system modeling tool to support variability modeling in SysML models. In addition, we use the `pure::variants` tool for variability modeling and management. The approach is demonstrated through an example from Volvo CE. The initial application suggests a potential improvement in efficiency of the engine development process.

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