Using mCRL2 for the analysis of software product lines

Citation for published version (APA):

Document status and date:
Published: 01/01/2014

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Using mCRL2 for the analysis of software product lines

Maurice H. Ter Beek and Erik P. De Vink

14/02

ISSN 0926-4515

All rights reserved
editors: prof.dr. P.M.E. De Bra
        prof.dr.ir. J.J. van Wijk

Reports are available at:
http://library.tue.nl/catalog/TUEPublication.csp?Language=dut&type=ComputerScienceReports&sort=Author&level=1
http://library.tue.nl/catalog/TUEPublication.csp?Language=dut&type=ComputerScienceReports&sort=Year&Level=1

Computer Science Reports 14-02
Eindhoven, March 2014
Using mCRL2 for the analysis of software product lines

Maurice H. ter Beek
ISTI–CNR, Pisa, Italy
maurice.terbeek@isti.cnr.it

Erik P. de Vink
Eindhoven University of Technology &
CWI, Amsterdam, The Netherlands
evink@win.tue.nl

ABSTRACT
We show how the formal specification language mCRL2 and its state-of-the-art toolset can be used successfully to model and analyze variability in software product lines. The mCRL2 toolset supports parametrized modeling, model reduction and quality assurance techniques like model checking. We present a proof-of-concept, which moreover illustrates the use of data in mCRL2 and also how to exploit its data language to manage feature attributes of software product lines and quantitative constraints between attributes and features.

Categories and Subject Descriptors
D.2.4 [Software Engineering]: Software/Program Verification—Formal methods, Model checking; D.2.13 [Software Engineering]: Reusable Software—Domain engineering

General Terms
Experimentation, Verification

Keywords
Model checking, product lines, variability analysis, mCRL2

1. INTRODUCTION
The last decades have witnessed a paradigm shift from mass production to mass customization in order to serve as many individual customer needs as possible. This has led to the emergence of Software Product Line Engineering (SPLE) [22], a software engineering approach aimed at cost-effectively developing a variety of software-intensive products that share a reference model, i.e., that together form a (software) product line. In SPLE, commonality and variability are defined in terms of features, which may be mandatory, optional or alternative, and managing variability means identifying variation points in a shared family model to encode exactly those combinations of features concerning valid products. Actual product configuration during application engineering is then reduced to selecting desired options in the variability model.

The most prominent variability model, a feature diagram, is a compact representation of all products of a product line in terms of features [24]. Graphically, features are nodes of a rooted tree and relations between them model constraints (mandatory, optional or alternative, but also, e.g., mutually exclusive). However, there may be hundreds of features, requiring models with hundreds of options, which easily leads to anomalies like superfluous or—worse—contradictory variability information (e.g., false optional or dead features). There is a large body of literature on computer-aided analyses of variability models to extract valid products and detect anomalies [5]. None of these analyses consider behavioral variability, though, meaning that only the presence of features is measured, not their causality or ordering in time.

Formal methods have successfully been applied in single product engineering for decades now with the aim of rigorously establishing critical system requirements. In SPLE, on the contrary, formal methods are not exploited that broadly, despite their potential to detect anomalies and to improve product quality. One reason is that mainstream formal methods do not consider variability directly. Still, in SPLE the correctness of artifacts intended for reuse as well as the correctness of the developed products is of crucial importance since many of them concern massively produced and safety- or business-critical applications. Remarkably, formal methods that have been applied in SPLE mainly focus on structural rather than behavioral properties.

To lay a basis for a formal analysis of product lines that does take behavior into account, it is important to formally model behavioral variability. After this was first recognized in the context of UML [17, 27], it has caused a growing interest in behavioral variability and the tailoring of several behavioral models for SPLE, which has given rise to variants of transition systems [11, 18, 19, 1, 7], process algebras [16, 12, 3], Petri nets [21], Event-B models [15] and state machines [20]. As a result, behavioral analysis techniques like model checking are recently being deployed for the verification of temporal properties over product lines [6, 4, 20].

In this paper, in line with the analysis recommendations of [2], we report on the feasibility of using the mCRL2 toolset for the analysis of software product lines. Whenever appropriate, connections with related approaches are mentioned, but a detailed comparison is left for future work. mCRL2 [10] is a formal, process-algebraic specification language with an associated industrial-strength toolset [13], specifically designed to reason on distributed and concurrent systems. It has been developed, improved and actively maintained for several years now and it strives for maximal user influence at every step during modeling and verification. System analysis with mCRL2 has been successfully applied in a wide range of academic and industrial case studies. Furthermore, mCRL2’s modeling language supports user-defined abstract datatypes that can be exploited to deal with feature attributes and associated quantitative constraints.

The body of this technical report appears in the Proceedings of the 2nd FME Workshop on Formal Methods in Software Engineering (FormaliSE’14), Hyderabad, India, IEEE. In this report, the mCRL2 code is included in the appendix.
2.运行示例产品线

我们的运行示例是一个咖啡机家族的扩展。它有以下列表的要求:

- 初始时，必须插入至少一个一欧元硬币，专门为欧洲产品，或至少一个一美元硬币，专门为加拿大产品。
- 输入的钱可以通过取消按钮取消。可选地，机器在按下一个按钮后改变状态，该按钮可以被按一次。
- 一旦机器被启动，至少一个一欧元或一美元被插入。
- 一旦机器被启动，至少一个一欧元或一美元被插入。
- 一旦机器被启动，至少一个一欧元或一美元被插入。
- 一旦机器被启动，至少一个一欧元或一美元被插入。
- 一旦机器被启动，至少一个一欧元或一美元被插入。
- 一旦机器被启动，至少一个一欧元或一美元被插入。
- 一旦机器被启动，至少一个一欧元或一美元被插入。

一种特征图是一个包含特征的层次结构，这些特征的组合可能影响产品的性能。这些特征可以是非必需的、可选的或强制性的。对于我们的示例，我们需要考虑特征图和产品线，以及它们之间的约束。特征图可以用来辅助产品线的建模和分析，特别是当有多个特征时。例如，如果我们有两个特征，A和B，那么特征图可以表示为:

```
Feature
A, B
```

3. The mCRL2 Language and Toolset

mCRL2 是一种形式化语言，它与一个工具集相结合，用于规格化和分析行为的分布式系统和协议 [13]。从其开发的早期，mCRL2 是一个活跃的维护和针对工业规模应用的中间件。该语言是基于过程代数 ACP 的。状态型数据类型可以用来参数化行为。mCRL2 旨在通过使用模型检查来提供最大化的灵活性。提交的设计模式和实现一致性检查，以及专门的优化技术，加上建模、仿真、行为简化和模型检查，都可以达到软件的其他部分。

The mCRL2 toolset was successfully applied in various settings. One of them concerns the massive data collection system used for the high-energy experiments conducted at the large hadron collider of CERN [23]. Parts of the system occasionally entered inconsistent states, leading to a loss of efficiency and a potential loss of data. Critical subsystems were modeled in mCRL2 and safety and liveness requirements were verified using model checking. These requirements stated, e.g., that jobs are always processed once submitted, and that jobs never enter an inconsistent state. Violations of these requirements revealed livelocks and race conditions, explaining phenomena observed in the actual system.

FlexRay 是一个广泛采用的通信协议在汽车工业。它旨在为提供一个可靠的、高带宽的通信通道之间的汽车组件。该协议是一个时间触发的，i.e.，它依靠组件来同步发生的时钟，并通过分配带宽基于一个全局的，周期性调度。FlexRay 启动程序，此过程确保活动组件将找到每个其他，并将正确初始化其本地视图在全局调度，被模型化并且被检查对正确性使用 mCRL2。[9]。该表达性的 mCRL2 允许作者的 [9]，以指定协议的正确性。

The robustness of FlexRay was analyzed by injecting faults that may occur in the system. This was implemented by making small, local changes to the fault-free model.

Documentation and binaries of the mCRL2 toolset can be downloaded at www.mcrl2.org. The toolset is open source; the associated boost license allows anyone free use for any purpose. For our approach to variability analysis, mCRL2's full expressiveness is not needed. We can resort to relatively simple structured models, extending the range of the tools. A trivial example is the labeled transition system (LTS) in Figure 2, which can be modeled by an mCRL2 process Foo with integer attribute as a parameter holding the state and with actions a-e. Part of the code for the Foo process looks like:
proc Foo(st:Int) =
( st==0 ) -> ( b.Foo(1) + a.Foo(2) ) +
( st==1 ) -> ( c.Foo(3) ) +
( st==2 ) -> ( b.Foo(1) + b.Foo(3) + a.Foo(4) ) +
...

Figure 1: Attributed feature model of the family of coffee machines (with shorthand names)

Figure 2: Example LTS

With mCRL2, a system property can be expressed as a formula in a variant of the modal μ-calculus [14]. Subsequently, the property can be verified against the specification using the model checking facilities of the mCRL2 toolset. Among the properties that hold for the specification above we mention:

- \( \text{true} \land \text{true} \rightarrow \text{true} \): absence of deadlock.
- \( \text{true} \land \text{b}. \text{true} \land \text{a}. \): after any sequence where the action b precedes the action a, false will hold. As the latter never holds the formula can be reformulated: no a-action is possible after a b-action has happened.
- \( \mu Y. (\langle c \rangle (\text{true}) Y) \): a least-fixed-point construction. Always, after a finite amount of steps a c-action can be done (or deadlock occurs earlier). The smallest set of states Y that can do a c-action or cannot step outside of Y, can be computed by iteration.
- \( \mu Y. ((\nu Z. (\langle b.d.e \rangle Z)) \langle \text{true} \rangle Y) \): a nesting of a least-fixed-point and a greatest-fixed-point construction. Always after a finite amount of steps an infinite repetition of b, d, and e is possible.

The modal μ-calculus, occasionally also dubbed the ‘Logic of Everything’, is known to be very expressive and to subsume other well-known temporal logics like LTL and (A)CTL. The process-algebraic approaches of [16, 3] propose multi-valued modal μ-calculus and LTL model checking, respectively, while that of [19] proposes CTL model checking. Only the approach of [3] is implemented, viz. in the Maude toolset (maude.cs.uiuc.edu). The appeal of the modal μ-calculus variant used in mCRL2 [14] is the possibility to quantify over data, as we shall see in the example product line below.

The general workflow for model checking with mCRL2 consists of (i) translating a specification foo.mcrl2 into a standard format called a linear process specification foo.lps. (ii) transforming the linear process together with the modal formula bar.mf to a so-called parametrized Boolean equation system foo.pbes and then solving it, yielding true or false for the formula bar.mf with respect to the specification foo.mcrl2. Alternatively, one can generate the underlying state space foo.lts of the specification to visually inspect it. The hiding of well-chosen actions and minimization with respect to one of the process equivalences offered by the toolset (like trace equivalence, weak and branching bisimulation) allows one to transform foo.lts and to focus on specific behavioral aspects of the specification. Using the latter technique, as will be illustrated in the next section, a state space with millions of states can be reduced substantially, bringing it in scope for human examination.

4. VERIFYING THE RUNNING EXAMPLE

In our approach to variability analysis we model a product line as an mCRL2 process. A product line can be represented as a combination of two finite state machines (FSMs). An initial FSM, whose behavior is transient, deals with feature selection. Its successful end states are in one-to-one correspondence with the consistent and complete configurations of the product line, and are the starting point for the FSM describing the actual behavior of a product. Therefore, the FSM takes an eligible set of features as an argument to model the particular instance of the product line with respect to the selected set of features. Only actions that are in agreement with these selected features will be executed.

We model the configuring of a product separate from its actual behavior (following [3]). The breadth-first node traversal of a feature diagram is directly translated into an FSM leading from the initial state to an end state. At this stage an end state is successful (but temporary) if the selected features meet the constraints of the feature model; other-
wise the end state is a deadlock state (or, alternatively, the starting point of a process that catches the error). To start with, the root feature is selected in the initial state. For our example the nodes of the feature diagram of Figure 1 are visited in the order S, O up to T to include all mandatory features and to select a number of optional features.

The full mCRL2 code can be found in the Appendix. We define a process Sel with parameters st and fs that hold, respectively, a state represented by an integer and a set of features included so far. The initial call to the process is Sel(0, [M]), i.e. the selection process starts in state 0 with only the root feature M selected. The mCRL2 code snippet below shows the inclusion of the mandatory feature O in state 1. The parameter st is incremented and the parameter fs is updated via the construct insert(0, fs), adding the feature O to the feature set under construction (with the mandatory feature S added in state 0, yielding [M, S, O]). In state 2 there is a choice since the O-feature is optional. If the feature O is not selected the silent action tau is taken, the state parameter st is incremented but the parameter fs is left unchanged. If, on the contrary, the feature R is selected, then the action setR is taken, and the parameters are updated accordingly.

```
proc Sel(st:Int, fs:FSet) =
  ... (st == 1) ->
    (M in fs) ->
      setO . Sel(2, insert(0, fs))
  ... +
  (st == 2) ->
    (M in fs) ->
      tau . Sel(3, fs) +
      setR . Sel(3, insert(R, fs))
  ... +
```

This leads to a number of deterministic actions for mandatory features, like setO, and non-deterministic actions for optional features, like tau and setR. After all nodes (leaves included) in the feature diagram have been visited, a resulting feature set fs still may or may not satisfy the cross-tree and attribute constraints of the (attributed) feature model.

The cross-tree constraints are considered next. In the code snippet below, the action wrong_set is taken to reject the selected feature set. If this action is executed, the process enters a deadlock state; there is no transition beyond delta. The first condition \((D in fs) \&\& (P in fs)\) captures that the D-feature and P-feature exclude each other, i.e. they cannot both be in an admissible feature set. The second condition \(! (R in fs) \&\& (P in fs)\) captures that the P-feature requires the R-feature, i.e. P cannot be in an admissible feature set if R is not. If the two tests fail, i.e. both additional constraints are met, then the action ctc_ok with the selected feature set fs as an argument is taken and the quantitative constraints on attributes are handled similarly.

```
(st == 8) ->
  ((D in fs) \&\& (P in fs)) ->
    wrong_set . delta <>
  (! (R in fs) \&\& (P in fs)) ->
    wrong_set . delta <>
  ctc_ok . Sel(0, fs)
```

In our example, a function tcosts calculates the total costs over the set of features fs. If this exceeds the threshold of 30, as expressed in the attributed feature model of Figure 1, the wrong_set action is taken to the deadlock state. If the total costs remain within bounds, the set_ok is taken and control is transferred from the feature selecting process Sel to the process Prod modeling the product behavior. Note that the feature set fs is passed as an argument of the action set_ok. This will prove useful for model checking purposes later.

Thus, the modeling of feature selection is guided by the feature diagram, while afterwards fulfillment of the cross-tree and of the attribute constraints is checked, in that order.

The actual behavior of the product is launched by the call Prod(0, fs) for a specific consistent and complete feature set fs, after execution of actions set_ok and cost by the selection process Sel. To model the behavior of our example we follow the LTS in Figure 3. This is the LTS from [1] extended with detailed money insertion handling. For conciseness, the box labelled Insert/Return abbreviates the sub-LTS concerning the latter. The process Prod thus starts with a call to the process Insert to enable money insertion.

Figure 3: LTS modeling family behavior

To reflect product configuration, we only allow an action if the feature it belongs to is part of fs (i.e. reminiscent of the way this is done in [7, 21, 3], we implicitly assume actions to be tagged with a feature). In the mCRL2 code we have, e.g.,

```
proc Prod(st:Int, fs:FSet) =
  (st == 0) ->
    (Insert(0, fs)) +
  ...
  (st == 2) ->
    (C in fs) -> coffee . Prod(4, fs) +
    (T in fs) -> tea . Prod(5, fs) +
    (P in fs) -> cappuccino . Prod(6, fs)
  ...
```
expressing that a coffee action is possible provided the (mandatory) \(C\)-feature is selected. Likewise for the tea and cappuccino actions (which do stem from optional features).

Handling coins is more involved and illustrates the use of data in \(mCRL2\). In our example, money is to be inserted until the balance is 100 cents or more, unless the cancel button is pressed earlier. In the latter case, the balance is returned. In the former case, control continues to the handling of sugar and beverage. However, with the change feature \(X\) selected, change may be returned. Otherwise no change will be given, as notified by the no_change action. Below, the code for the process Insert is given. The process has two parameters: bal holding the balance and \(fs\) holding the selected features.

```plaintext
proc Insert(bal:Nat,fs:FSet) =
( bal < 100 ) ->
( ( D in fs ) ->
  insert(dime) . Insert(bal+10,fs) +
  insert(quarter) . Insert(bal+25,fs) +
  insert(half) . Insert(bal+50,fs) +
  insert(dollar) . Insert(bal+100,fs) ) +
( E in fs ) ->
  ( insert(ct10) . Insert(bal+10,fs) +
    insert(ct20) . Insert(bal+20,fs) +
    insert(ct50) . Insert(bal+50,fs) +
    insert(euro) . Insert(bal+100,fs) ) ) +
( ( bal > 0 ) && ( bal < 100 ) ) ->
  Return(bal,fs).cancel . Prod(0,fs) +
( bal >= 100 ) ->
  ( ( !(X in fs) ) ->
    no_change . continue . Prod(1,fs) <>
   Return(Int2Nat(bal-100),fs) .
   continue . Prod(1,fs) )
)
```

For a balance less than 100 cents, insertion of a specific coin is coupled to an update of the balance. Only coins of the right currency are accepted. Note that this assumes that an eligible feature set \(fs\), which was passed by the Sel process, contains either \(D\) or \(E\). For the action cancel, the balance is returned via a call to Return and control returns to the initial state Prod(0,fs). If, on the other hand, the balance has grown sufficiently, control proceeds to the state Prod(1,fs) via the continue action. Furthermore, in case change is returned, 100 cents are subtracted from the balance first.

Characteristic for process-algebraic approaches, including \(mCRL2\), is the availability of hiding. One can abstract away a subset of actions to focus on the behavior built from the remaining ones. Moreover, as with \(mCRL2\) all intermediate artifacts are available to the user, these can be manipulated to the user’s liking, possibly with the help of the many tools available in the toolset. For instance, when the actions of configuring the product and those related to payment are abstracted away, and the result is minimized with respect to a process equivalence like weak trace equivalence, then the state space depicted in Figure 4 is obtained. The actual behavior of such an abstracted product consists of a sequence of actions starting with a sugar or no_sugar action and ending with a take_cup action.

Starting from the initial state, one out of six cyclic behaviors is reached: four products with coffee only and no ringtone (varying in dollar or euro currency and the availability of change) and four products with coffee only but with a ringtone (and similar variations for the other features); four products with coffee and tea but with a ringtone; one product with coffee, cappuccino and a ringtone, and one product with coffee, tea, cappuccino and a ringtone. This way, by visual inspection of part of the state space, viz. the part remaining after hiding and minimization, one may verify that a product with cappuccino indeed provides a ringtone as well. In general, by these reduction techniques large state spaces can be tuned to inspect specific, not necessarily local, behavior.

The property language of \(mCRL2\) is first-order and thus allows to incorporate data. To show what can be considered for variability analysis using the modal \(\mu\)-calculus, we discuss the following properties of our example product line:

- \([(!continue)*.take_cup] false\): if payment is not settled by action continue, no beverage is delivered.
- \([true*.setX.true*.no_change] false\): once the \(X\)-feature is selected, action no_change will not occur.
- \([true*.setOk(fs).*true*.no_change] false\): once the \(X\)-feature is selected, action no_change will not occur.
- \([true*.setOk(fs).*true*.val(D in fs) => !\(P in fs\)]:\) if a product is configured successfully as indicated by the set_ok action, then it cannot be a product that accepts dollars and also provides cappuccino.

Figure 4: Product behavior with configuration and payment abstracted away
The first property only concerns the actual behavior of any eligible product. The second relates an action in the configuration phase, set ok, and an action in the behavior phase, no_change. The third property involves a quantification over all possible configurable feature sets, which shows the aforementioned usefulness of passing the feature set \( fs \) as an argument of set_ok. The casts \( \text{val} \) are needed to yield a Boolean value. The last two properties involve a minimal fixed point over the formal variable \( Y \). In the fourth property the existential quantification is framed within the modality as no further reference to the actual feature set is needed.

The above describes the basic setup for our approach of using mCRL2 for variability analysis; several extensions of the basic scheme are possible. (i) For instance, similar to the way this is done in [3], dynamic feature management can be arranged for by adding transitions from the \( \text{Prod} \) process to the \( \text{Sel} \) process and back again to \( \text{Prod} \) to deal with feature selection on-the-fly. (ii) Here, we followed a strict order for feature selection: first the feature diagram was taken into account, then cross-tree constraints were considered and finally quantitative (attribute) constraints were checked. When dealing with many more features, it is likely advantageous to do this in a more flexible way, so as to rule out inconsistent feature sets at an early stage during selection. Clearly, any of the additional constraints can be checked as soon as all features involved have been selected or not. Even more refined selection schemes traversing the tree associated with the feature diagram can be modeled as well. (iii) As a final variation we mention the possibility to tweak the feature selection process and have it enumerate subfamilies, e.g. containing the products satisfying all requirements or those violating a specific family requirement, to gain insight in the relation between specific constraints and subsets of features. This can be achieved by stealing control at the corresponding point of the selection process and to transfer to a proper signaling process.

On a final note, because of the open workflow with mCRL2, any output of the toolset can be exported to other tools, e.g. SAT/SMT-solvers. Reversely, specific feature settings, e.g. resulting from other means of analysis, can be used as a starting point by jumping to the right state of the \( \text{Sel} \) or \( \text{Prod} \) process. The crucial point is that we perform product line analysis within the framework of a full-fledged verification toolset while maintaining control of the design choices to be made during modeling and of the properties to verify. Still, larger case studies need to be done to assess the scalability of our setup, in particular regarding model checking.

Several of the behavioral variability models mentioned in Sect. 1 have an associated tool for behavioral variability analysis with verification techniques like model checking. \text{SNIP} [6] is a model checker for product lines modeled as featured transition systems (FTSs) specified in a language based on that of the SPIN model checker (spinroot.com). The feature diagram is coded in the textual variability language TVL to be consulted by the explicit-state on-the-fly model-checking algorithm of \text{SNIP} to verify properties expressed in so-called feature LTL interpreted over FTSs (e.g. to verify a property over only a subset of the valid products).

Symbolic FTS model checking was implemented as an extension of the NuSMV model checker (nusmv.fbk.eu) with a fully symbolic algorithm for feature CTL, as it is called. In \text{SNIP}, special-purpose exhaustive model checking algorithms (continuing a search also after a violation was found) allow the user to verify all products of a product line at once and to output counterexamples for all products that violate a property (in contrast with the NuSMV extension that only produces a counterexample for the first violating product found). \text{SNIP} has recently been re-engineered and the resulting tool suite ProVeLines can handle feature attributes [8].

\text{VMC} [4] (fmt.isti.cnr.it/vmc) is a model checker for product lines modeled as modal transition systems (MTSs) with added variability constraints, but with no specific reference to feature diagrams. \text{VMC} offers automatic generation of one/some/all valid products (modeled as LTSs) of a product line. The user can simulate, visualize or model check either the full product line or a set of its valid products. \text{VMC}'s explicit-state on-the-fly model-checking algorithm allows the verification of properties expressed in so-called variability-CTL interpreted over MTSs, it moreover offers the possibility to inspect the (interactive) explanations of a verification result. An extension handling data is forthcoming.

In [20], FMSs are extended with variability by means of guards over variables on transitions and a global predicate defining the valid configurations by value assignments. For each product line feature, two FMSs are built, one for the requirements and one for the design level, and it is specified how to check their conformance. The prototype tool \text{SPLEnD} transforms pairs of XML files for the FMSs into a file that can be fed to \text{SPIN}, which either returns the conformance mappings or declares nonconformance. In the latter case, the behavior of the product line can be checked by SAT solving. As far as we know, \text{SPLEnD} does not cater for feature attributes.

5. CONCLUDING REMARKS

We have presented a proof-of-concept for formal variability analysis with mCRL2, highlighting its main features concerning both modeling (e.g. parametrized processes, data handling) and analysis (e.g. minimization techniques, model checking properties in the modal \( \mu \)-calculus with data).

Most model-checking analyses described in this paper fall in the category of product-based analyses, i.e. operating on individually generated products (or at most a subset) [26]. This contrasts with family-based analyses, operating on an entire product line at once using variability knowledge about valid feature configurations to deduce results for products, of which \text{SNIP} is a well-known and successful representative. \text{VFC} offers the full spectrum of analyses, but—contrary to the special-purpose FTS model-checking algorithms of \text{SNIP}—when a formula is verified over an entire product line, then a negative result does not actually list the specific products in...
which the property fails to hold. However, both in VMC and in mCRL2, the full list of violating products can be obtained by model checking the formula against each individual product of the product line (inspection of a counterexample reveals one violating product only).

There might be a trade-off between brute-force product-based analysis with model checkers that have been highly optimized for single system engineering, like SPIN and—
to a lesser degree—mCRL2, and highly innovative family-based analysis with model checkers that have been developed specifically for product lines, like SNIP. In fact, SPIN generally outperforms SNIP [6] (according to the authors of [6] this is due to SPIN’s many optimizations, among which partial order reduction). In this respect, an evaluation of the state-of-the-art mCRL2 toolset, which may lead to the desire to implement some product line-specific features into its model-checking algorithms, is left for future work.

6. ACKNOWLEDGMENTS
Maurice ter Beek conducted part of this work while on sabbatical leave at Leiden University. He gratefully acknowledges the hospitality and support of the Leiden Institute of Advanced Computer Science during his stay in Leiden. Maurice ter Beek also acknowledges support of the EU FP7-ICT FET-Proactive project QUANTICOL (600708) and of the Italian MIUR project CINA (PRIN 2010LHT4KM).

7. REFERENCES
APPENDIX

A. mCRL2 SPECIFICATION OF EXAMPLE

%% mCRL2 specification of the running example
%% variation of coffee machine with change feature,
%% cost attribute and handling of coins

sort
Feature = struct
    M | S | O | R | B | X | D | E | P | T | C ;
FSet = List( Feature ) ;
Coin = struct
dime | quarter | half | dollar |
ct10 | ct20 | ct50 | euro ;
Currency = struct Dollar | Euro ;

act
insert, return : Coin ;
continue, cancel, sorry, no_change,
sugar, no_sugar, coffee, cappuccino,
pour_sugar, pour_milk, pour_coffee, pour_tea,
ingo, skip, take_cup ;
setS, setO, setR, setB, setX,
setD, setE, setP, setT, setTP, setC ;
wrong_set, ctc_ok ;
set_ok : FSet ;
cost : Int ;

map
isSorted: FSet -> Bool;
noDuplicates: FSet -> Bool;
isSet: FSet -> Bool;

var
ft, ft' : Feature; fset, fset' : FSet;

eqn
isSorted([]) = true;
isSorted([ft]) = true;
isSorted(ft |> (ft' |> fset)) =
    ft <= ft' & & isSorted(ft' |> fset);
noDuplicates([]) = true;
noDuplicates(ft |> fset) =
    !(ft in fset) & & noDuplicates(fset);
isSet(fset) =
    isSorted(fset) & & noDuplicates(fset);

map
insert: Feature # FSet -> FSet;

var
ft, ft' : Feature; fset, fset' : FSet;


eqn
insert(ft, []) = [ft];
(insert(ft, ft' |> fset) =
    ft' |> fset;
(insert(ft, ft' |> fset) =
    ft' |> fset;
(insert(ft, ft' |> fset) =
    ft' |> fset;

map
union: FSet # FSet -> FSet;

var
ft, ft' : Feature; fset, fset' : FSet;

eqn
union([], fset) = fset;
union(fset, []) = fset;
(union(ft |> fset, ft' |> fset') =
    ft |> union(fset, ft' |> fset'));
(union(ft |> fset, ft' |> fset') =
    ft' |> union(fset, fset');
union(ft |> fset, ft' |> fset') =
    ft' |> union(fset, fset');

map
cost : Feature -> Int ;

eqn
fcost(M) = 0 ;
fcost(S) = 5 ;
fcost(O) = 0 ;
fcost(B) = 0 ;
fcost(R) = 5 ;
fcost(D) = 5 ;
fcost(E) = 5 ;
fcost(X) = 10 ;
fcost(C) = 5 ;
fcost(T) = 3 ;
fcost(P) = 7 ;

map
tcost : FSet -> Int ;

var
ft : Feature; fset : FSet;

eqn
tcost([]) = 0;
tcost(ft |> fset) = fcost(ft) + tcost(fset);

proc Sel(st:Int, fs:FSet) =
%% feature states
(st == 0) ->
    (M in fs) ->
        (setS . Sel(1, insert(S, fs)) )
    ) +
(st == 1) ->
    (M in fs) ->
        (setO . Sel(2, insert(O, fs)) )
    ) +
(st == 2) ->
    (M in fs) ->
        (tau . Sel(3, fs) +
         setR . Sel(3, insert(R, fs)) )
    ) +
(st == 3) ->
    (M in fs) ->
        (setB . Sel(4, insert(B, fs)) )
    ) +
(st == 4) ->
    (M in fs) ->
        (tau . Sel(5, fs) +
         setX . Sel(5, insert(X, fs)) )
    ) +
(st == 5) ->
    (0 in fs) ->
        (setD . Sel(6, insert(D, fs)) +
         setE . Sel(6, insert(E, fs)) )
    ) +
init
Sel(0,[M])

proc Prod(st:Int,fs:FSet) =
( st == 0 ) -> ( Insert(0,fs) )
+ ( st == 1 ) -> ( ( S in fs ) -> ( sugar . Prod(2,fs) ) + ( S in fs ) -> ( no_sugar . Prod(3,fs) ) )
+ ( st == 2 ) -> ( ( C in fs ) -> coffee . Prod(4,fs) + ( T in fs ) -> tea . Prod(5,fs) + ( P in fs ) -> cappuccino . Prod(6,fs) )
+ ( st == 3 ) -> ( ( C in fs ) -> coffee . Prod(9,fs) + ( T in fs ) -> tea . Prod(8,fs) + ( P in fs ) -> cappuccino . Prod(7,fs) )
+ ( st == 4 ) -> ( ( M in fs ) -> ( pour_sugar . Prod(9,fs) ) )
+ ( st == 5 ) -> ( ( M in fs ) -> ( pour_sugar . Prod(8,fs) ) )
+ ( st == 6 ) -> ( ( M in fs ) -> ( pour_sugar . Prod(7,fs) ) )
+ ( st == 7 ) -> ( ( M in fs ) -> ( pour_milk . Prod(10,fs) ) + ( M in fs ) -> ( pour_coffee . Prod(11,fs) ) )
+ ( st == 8 ) -> ( ( M in fs ) -> ( pour_teas . Prod(12,fs) ) )
+ ( st == 9 ) -> ( ( M in fs ) -> ( pour_coffee . Prod(12,fs) ) )
+ ( st == 10 ) -> ( ( M in fs ) -> ( pour_coffee . Prod(12,fs) ) )
+ ( st == 11 ) -> ( ( M in fs ) -> ( pour_milk . Prod(12,fs) ) )
+ ( st == 12 ) -> ( ( R in fs ) -> ( ring . Prod(13,fs) ) + (! ( R in fs ) ) -> ( skip . Prod(13,fs) ) )
+ ( st == 13 ) -> ( ( M in fs ) -> ( take_cup . Prod(0,fs) ) )
);

proc Insert(bal:Nat,fs:FSet) =
( bal < 100 ) -> ( ( D in fs ) -> ( insert(dime) . Insert(bal+10,fs) + insert(quarter) . Insert(bal+25,fs) + insert(half) . Insert(bal+50,fs) + insert(dollar) . Insert(bal+100,fs) ) + ( E in fs ) -> ( insert(ct10) . Insert(bal+10,fs) + insert(ct20) . Insert(bal+20,fs) + insert(ct50) . Insert(bal+50,fs) + insert(euro) . Insert(bal+100,fs) ) )
+ ( ( bal > 0 ) && ( bal < 100 ) ) -> Return(bal,fs) . cancel . Prod(0,fs) + ( bal >= 100 ) -> ( ( ! ( X in fs ) ) -> no_change . continue . Prod(1,fs) <> Return(Int2Nat(bal-100),fs) . continue . Prod(1,fs) )
);

proc Return(bal:Nat,fs:FSet) =
( bal == 0 ) -> tau + ( D in fs ) -> ( ( bal >= 50 ) -> return(half) . Return(bal-50,fs) + ( ( bal < 50 ) && ( bal >= 25 ) ) -> return(half) . Return(bal-25,fs) + ( ( bal < 25 ) && ( bal >= 10 ) ) -> return(dime) . Return(bal-10,fs) + ( ( bal < 10 ) && ( bal > 0 ) ) -> sorry . Return(0,fs) )
+ ( E in fs ) -> ( ( bal >= 50 ) -> return(ct50) . Return(bal-50,fs) + ( ( bal < 50 ) && ( bal >= 20 ) ) -> return(ct20) . Return(bal-20,fs) + ( ( bal < 20 ) && ( bal > 0 ) ) -> return(ct10) . Return(bal-10,fs) + ( ( bal < 10 ) && ( bal > 0 ) ) -> sorry . Return(0,fs) )
);

% cross-tree constraints
( st == 8 ) -> ( ( D in fs ) && ( P in fs ) ) -> wrong_set . delta <>
( !( R in fs ) && ( P in fs ) ) -> wrong_set . delta <>
ctc_ok . Sel(9,fs)
+ % attribute constraints
( st == 9 ) -> ( tcost(fs) <= 30 ) -> set_ok( fs ) . cost( tcost(fs) ) . Prod(0,fs) <>
wrong_set . delta;
\%\% example system properties

\mu X.(
  < exists fs:FSet . set_ok(fs) > true ||
  < wrong_set > true ||
  [ true ] X )
[ true* . setX . true* . no_change ] false

\%\% this is a nice one :) 
[ true* . setE . true* . sorry ] false

\%\% next one is false, that is correct 
[ true* . setD . true* . sorry ] false

[ true* . insert(ct20) ]
\mu X.( < cancel || take_cup > true || [ true ] X )

forall c:Coin .
[ true* . insert(c) ]
\mu X.( < cancel || take_cup > true || [ true ] X )

[ true* ] forall c:Coin . [ insert(c) ]
\mu X.( < cancel || take_cup > true || [ true ] X )

\%\% this one is OK
forall fs:FSet . val(isSet(fs)) =>
  [ true* . set_ok(fs) . true* ] < true > true

\%\% but this equivalent one is verified much quicker
[ true* . (exists fs: FSet . set_ok(fs)) . true* ]
< true > true

forall fs:FSet .
val(isSet(fs)) && [ true* . set_ok(fs) ] true =>
  val((D in fs) => !(P in fs))

[ (!continue)* . take_cup ] false
[ true* . take_cup . (!continue)* . take_cup ] false

[ true* ] forall n:Nat . [ cost(n) ] ( val(n <= 30) )
In this series appeared (from 2012):

12/01  S. Cranen  Model checking the FlexRay startup phase
12/02  U. Khadim and P.J.L. Cuijpers  Appendix C / G of the paper: Repairing Time-Determinism in the Process Algebra for Hybrid Systems ACP
12/03  M.M.H.P. van den Heuvel, P.J.L. Cuijpers, J.J. Lukkien and N.W. Fisher  Revised budget allocations for fixed-priority-scheduled periodic resources
12/04  Ammar Osaiweran, Tom Fransen, Jan Friso Groote and Bart van Rijnsoever  Experience Report on Designing and Developing Control Components using Formal Methods
12/05  Sjoerd Cranen, Jeroen J.A. Keiren and Tim A.C. Willemse  A cure for stuttering parity games
12/06  A.P. van der Meer  CIF MSOS type system
12/07  Dirk Fahland and Robert Prüfer  Data and Abstraction for Scenario-Based Modeling with Petri Nets
12/08  Luc Engelen and Anton Wijs  Checking Property Preservation of Refining Transformations for Model-Driven Development
12/09  M.M.H.P. van den Heuvel, M. Behnam, R.J. Bril, J.J. Lukkien and T. Nolte  Opaque analysis for resource-sharing components in hierarchical real-time systems - extended version –
12/10  Milosh Stollijk, Pieter J. L. Cuijpers and Johan J. Lukkien  Efficient reprogramming of sensor networks using incremental updates and data compression
12/11  John Businge, Alexander Serebrenik and Mark van den Brand  Survival of Eclipse Third-party Plug-ins
12/12  Jeroen J.A. Keiren and Martijn D. Klabbers  Modelling and verifying IEEE Std 11073-20601 session setup using mCRL2
12/13  Ammar Osaiweran, Jan Friso Groote, Mathijs Schuts, Jozef Hooman and Bart van Rijnsoever  Evaluating the Effect of Formal Techniques in Industry
12/14  Ammar Osaiweran, Mathijs Schuts, and Jozef Hooman  Incorporating Formal Techniques into Industrial Practice
13/01  S. Cranen, M.W. Gazda, J.W. Wesselink and T.A.C. Willemse  Abstraction in Parameterised Boolean Equation Systems
13/02  Neda Noroozi, Mohammad Reza Mousavi and Tim A.C. Willemse  Decomposability in Formal Conformance Testing
13/03  D. Bera, K.M. van Hee and N. Sidorova  Discrete Timed Petri nets
13/04  A. Kota Gopalakrishna, T. Ozelebi, A. Liotta and J.J. Lukkien  Relevance as a Metric for Evaluating Machine Learning Algorithms
13/05  T. Ozelebi, A. Weffers-Albu and J.J. Lukkien  Proceedings of the 2012 Workshop on Ambient Intelligence Infrastructures (WAmI)
13/06  Lotfi ben Othmane, Pelin Angin, Harold Weffers and Bharat Bhargava  Extending the Agile Development Process to Develop Acceptably Secure Software
13/08  Mark van den Brand and Jan Friso Groote  Software Engineering: Redundancy is Key
13/09  P.J.L. Cuijpers  Prefix Orders as a General Model of Dynamics
14/01 Jan Friso Groote, Remco van der Hofstad and Matthias Raffelsieper  On the Random Structure of Behavioural Transition Systems

14/02 Maurice H. ter Beek and Erik P. de Vink  Using mCRL2 for the analysis of software product lines