Combining Declarative and Procedural Views in the Specification and Analysis of Product Families

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ABSTRACT

We introduce the feature-oriented language FLAN as a proof of concept for specifying both declarative aspects of product families, namely constraints on their features, and procedural aspects, namely design processes and run-time behaviour. FLAN is inspired by the concurrent constraint programming paradigm. A store of constraints allows one to specify in a declarative way all common constraints on features, including cross-tree constraints as known from feature models. A standard yet rich set of process-algebraic operators allows one to specify in a procedural way the configuration and behaviour of products. There is a close interaction between both views: (i) the execution of a process is constrained by its store to forbid undesired configurations; (ii) a process can query a store to resolve design and behavioural choices; (iii) a process can update the store, for instance to add new features. An implementation in the Maude framework allows for a variety of formal automated analyses of product families specified in FLAN, ranging from consistency checking to model checking.

Categories and Subject Descriptors

D.2.4 [Software Engineering]: Software/Program Verification—Formal methods, Model checking, Validation

General Terms

Design, Experimentation, Verification

Keywords

Product families, Variability, Process algebra, Concurrent constraint programming, Behavioural analyses, Maude

1. INTRODUCTION

Research on applying formal methods in SPLE traditionally focuses on modelling and analysing structural rather than behavioural constraints in product families. However, many software-intensive systems are embedded, distributed and critical, making it important to be able to model and analyse also their behaviour, as a form of quality assurance. Recent years have witnessed a growing interest in specifically considering also the behavioural variability of product families. This has resulted in variants of UML diagrams [31], extensions of Petri nets [25, 26] and a variety of frameworks with transition system semantics [12, 18, 15, 20, 10, 8]. As a result, behavioural analysis techniques such as model checking have become available for the verification of (temporal) logic properties of product families.

Specifying a product family directly in an operational model is often not easily feasible. Therefore it can be useful to resort to high-level formal languages with semantics over those operational models, as is common in the context of process algebra. Several extensions of CCS [24] have been proposed to model product families [13, 15, 16, 21], but none of these can combine behavioural constraints with all common structural constraints known from feature models.

We introduce here the feature-oriented language FLAN as a proof of concept for specifying product families by taking both structural and behavioural constraints into account. It is inspired by concurrent constraint programming [28] and its application in process algebra [8]. A store of constraints allows one to specify in a declarative way all common structural constraints known from feature models, including cross-tree constraints. Moreover, a rich set of process-algebraic operators allows one to specify in a procedural way both the configuration and behaviour of products.

The declarative and procedural views are closely related: (i) the execution of a process is constrained by its store, e.g. to avoid introducing inconsistencies; (ii) a process can query a store to resolve options regarding the design and behaviour; (iii) a process can update the store, e.g. to add new features.

Inspired by [13], we implemented FLAN in the executable modelling language Maude [11], whose rich toolkit enables the application of a variety of formal automated analysis techniques to product families specified in FLAN, from consistency checking to model checking.

The paper is organised as follows. Section 2 describes a running example of a family of coffee machines. In Sect. 3 we present the syntax and semantics of FLAN and a specification of the example. Section 4 illustrates the Maude-supported automated analyses of the example. We discuss related work in Sect. 5 and report some concluding remarks in Sect. 6 and list promising future work in Sect. 7.

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1 For the convenience of the reviewers the manuscript in [4] contains the complete Maude implementation.
2. A FAMILY OF COFFEE MACHINES

We use a popular running example in the style of [2], [3], [5], [6, 10, 13, 25, 26]. It describes a (simplified) family of coffee machines in terms of the following list of requirements:

1. Initially, a coin must be inserted: either a euro, exclusively for products for the European market, or a dollar, exclusively for Canadian products;
2. Upon the insertion of a coin, a choice for sugar must be offered, followed by a choice of beverages;
3. The choice of beverage (coffee, tea, cappuccino) varies, but every product must offer at least one beverage, tea may be offered only by European products, and all products that offer cappuccino must also offer coffee;
4. Optionally, a ringtone may be rung after the delivery of a beverage. However, a ringtone must be rung after serving a cappuccino;
5. After the beverage is taken, the machine returns idle.

These requirements define products by combining structural constraints defining valid feature configurations (e.g. “every product must offer at least one beverage”) with temporal constraints defining valid behaviour, i.e. action sequences (e.g. “a ringtone must be rung after serving a cappuccino”).

3. FLAN: SYNTAX AND SEMANTICS

The feature-oriented language FLAN we propose here is loosely inspired by the CCS-like process algebra CL4SPL presented in [13], but it strongly differs in its treatment of the cross-tree constraints known from feature models and in the separation of declarative and procedural aspects inspired by the concurrent constraint programming paradigm [28] and its adoption in process calculi [3].

The core notions of FLAN are features, constraints, processes and fragments, which can all be identified in the syntax of FLAN given in Fig. 1. More precisely, features range over f and g and constraints, processes and fragments correspond to the syntactic categories S, P and F, respectively.

**Features.** A feature is a term describing specific elements or properties of a product. The universe of features is denoted by \( \mathcal{F} \). The features of our running example are the coins accepted (i.e. euro and dollar), the products offered (i.e. coffee, tea and cappuccino) and additional elements such as sugar (the capability to regulate the quantity of sugar) and ringtone (the capability to emit a ringtone).

**Constraints.** The declarative part of FLAN is represented by a store of constraints which defines both constraints on features extracted from the product requirements and additional information (e.g. about the context wherein the product will operate).

Two important notions of constraint stores are (i) the consistency of a store \( S \), denoted \( \text{consistent}(S) \) and which in our case amounts to logical satisfiability of all constraints forming \( S \); and (ii) entailment \( S \models c \) of constraint \( c \) in store \( S \), which in our case amounts to logical entailment.

A constraint store is any term generated by \( S \) in the grammar of FLAN. The most basic constraint stores are \( \top \) (no constraint at all), \( \bot \) (inconsistent) and ordinary boolean propositions (generated by \( K \)). Constraints can be combined by juxtaposition (its semantics amounts to logical conjunction).

We assume that the standard structural constraints on features (like options, obligations and alternatives) are expressed using boolean propositions (e.g. as explained in [29]). For this purpose, we assume that the universe \( \mathcal{P} \) of propositions contains a Boolean predicate \( \text{has}(\cdot): \mathcal{F} \to \mathbb{B} \) that can be used (in grounded form) to denote the presence of a feature in a product. Boolean propositions can also be used to represent additional information such as contextual facts. Examples from our running example are \( \text{in(Europe)} \) and \( \text{in(Canada)} \), respectively used to state the fact that the coffee machine being configured is meant to be used in Europe or in Canada. Boolean propositions can state relations between contextual information and features, like \( \text{in(Europe)} \rightarrow \text{has(euro)} \) (i.e. a coffee machine for the European market needs a euro coin slot).

**Cross-tree constraints,** instead, are handled as first-class citizens. A constraint \( f \bowtie g \) expresses that feature \( f \) requires the presence of feature \( g \) while a constraint \( f \otimes g \) expresses that features \( f \) and \( g \) mutually exclude each other’s presence (i.e. they are incompatible). Of course, also these constraints can be encoded as boolean propositions. For instance, \( f \otimes g \) and \( f \bowtie g \) can equivalently be expressed as \( \text{has}(f) \leftrightarrow \neg\text{has}(g) \) and \( \text{has}(f) \rightarrow \text{has}(g) \). We use indeed such logical encoding to reduce consistency checking and entailment to logical satisfiability (and hence exploit Maude’s SAT solver). However, we prefer to keep here this first-class treatment in order to emphasize their use in the presentation of our work.

We also consider a class of action constraints, reminiscent of Featured Transitions Systems [10], where transitions are subject to the presence of features. For instance, in a coffee machine equipped with a slot for euro coins we will use \( \text{euro} \) for the action of inserting a euro coin and \( \text{do(euro)} \) as a proposition stating the execution of that action. The relations between the action \( \text{euro} \) and the presence of the corresponding feature \( \text{euro} \) can be formalised as \( \text{do(euro)} \rightarrow \text{has(euro)} \), i.e. the insertion of a euro coin requires the presence of an appropriate coin slot. In general, we assume that each action \( a \) may have a constraint \( \text{do(a)} \rightarrow p \). Such constraints act as a sort of guard to allow or forbid the execution of actions (as illustrated later on in the discussion of rule Act).

The constraint store \( S \) in Fig. 1 formalises part of the requirements specified in Sect. 2 for our running example. It contains both contextual information (e.g. \( \text{in(Europe)} \)) and action constraints (e.g. \( \text{do(euro)} \rightarrow \text{has(euro)} \)). For instance, from requirement 1 we extract that \( \text{euro} \) and \( \text{dollar} \) are mutually exclusive features. (formalised as \( \text{dollar} \otimes \text{euro} \))

\[
\begin{align*}
F &= [S \parallel P] \\
S,T &= K \mid f \bowtie g \mid f \otimes g \mid S \parallel T \mid \top \mid \bot \\
P,Q &= f \cdot X \mid \text{A.P} \mid P + Q \mid P ; Q \mid P \mid Q \\
A &= \text{install}(f) \mid \text{ask}(K) \mid a \\
K &= p \mid \neg K \mid K \lor K \\
\end{align*}
\]

where \( a \in A, p \in P \) and \( f, g \in \mathcal{F} \)
posed by a store of constraints

Section relation

duction semantics) is formalised in terms of the state transi-
turn, may condition the execution of process actions.

Finally, a cappuccino

coffee

A

actions (from a universe

It is worth remarking that we distinguish between ordinary

to identify different ways of denoting the same fragment.

We also assume that recursively defined processes are

there is a set of process definitions of the form \( X \overset{\mathcal{A}}{\to} P \).

We also assume that recursively defined processes are

modular. This choice of axioms (some of which may seem un-

usual) is not accidental. Indeed, all can be naturally and

efficiently treated by Maude so that our semantics enjoys sev-

eral nice properties: (1) it is (efficiently) executable; (2) each

semantic rule of Fig. 3 corresponds to exactly one condi-
tional rewrite rule in the Maude implementation of FLan;

(3) the number of reduction rules is small and the semantics

and its implementation are thus compact and easy to read.

As usual, reduction rules are expressed in terms of a set of

(possibly empty) premises (above the line) and a conclusion

(below the line).

Rules Inst and Act are very similar, both allowing a pro-

cess to execute an action if certain constraints are satisfied.

In particular, rule Inst forbids inconsistencies due to the

introduction of new features. Note that rule Inst can be

seen as a particular instance of the rule for the tell opera-
tion of concurrent constraint programming \([28]\) instantiated as
tell(has(f)).

Rule Act forbids inconsistencies with respect to action

constraints. We remark that a typical case of action con-

straint is \( do(a) \to has(f), \) i.e. action \( a \) is subject to the

presence of feature \( f \). However, this does not necessarily

mean that feature \( f \) has been explicitly installed: its pre-

sence may be derived as a consequence of further constraints.

This would be the case, for instance, of a store containing

the constraints \( g \triangleright f \) and has(g).

Rule Ask formalises the semantics of the usual ask(\( \cdot \))

operation as known from concurrent constraint program-

ning \([28]\). It allows to block a process until a proposition

can be derived from the store.

Rule Or is quite straightforward. It allows the process to

 evolve as any of the branches. It is worth remarking that

non-determinism can be solved at the procedural level (by

relying on ask(\( \cdot \)) actions) or at the declarative level (by

using a non-deterministic choice that may be solved by the con-

straint store).

Finally, a fragment \( F \) is a term \([S \parallel P]\), com-

posed by a store of constraints \( S \) and a process \( P \).

Each of the components of a fragment may influence each other,

along the lines of the concurrent constraint programming

paradigm \([28]\): a process may update its store which, in

turn, may condition the execution of process actions.

The operational semantics of closed fragments (i.e. its re-
duction semantics) is formalised in terms of the state transi-
tion relation \( \to \subseteq \mathcal{F} \times \mathcal{F} \) illustrated in Fig. 2,

where \( \mathcal{F} \) denotes the set of all terms generated by \( \mathcal{F} \) in the grammar of Fig. 4.

Technically, such reduction relation is defined in Structural

Operational Semantics (SOS) style (i.e. by induction on the

structure of the terms denoting a fragment) modulo a struc-
tural congruence relation \( \equiv \subseteq F \times F \). As usual, the reduction

relation implicitly defines an unlabelled transition system.

Considering terms up to a structural congruence allows to

identify different ways of denoting the same fragment.

Here we consider the least congruence on fragments closed

with respect to the commutativity and associativity of non-
deterministic and parallel composition of processes; the asso-
ciativity of sequential composition of processes; the identity

of non-deterministic choice, sequential and parallel composi-
tion of processes; and the expansion of recursive process def-

initions. This choice of axioms (some of which may seem un-

usual) is not accidental. Indeed, all can be naturally and

efficiently treated by Maude so that our semantics enjoys sev-

eral nice properties: (1) it is (efficiently) executable; (2) each

semantic rule of Fig. 3 corresponds to exactly one condi-
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straint is \( do(a) \to has(f), \) i.e. action \( a \) is subject to the

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sence may be derived as a consequence of further constraints.

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operation as known from concurrent constraint program-

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can be derived from the store.

Rule Or is quite straightforward. It allows the process to

 evolve as any of the branches. It is worth remarking that

non-determinism can be solved at the procedural level (by

relying on ask(\( \cdot \)) actions) or at the declarative level (by

using a non-deterministic choice that may be solved by the con-

straint store), thus providing a lot of flexibility to fragment

designers (as illustrated later on).
Figure 4: Initial specification of the coffee machine

Rules SEQ and PAR are standard. The former formalises the usual sequential composition, while the latter formalises an interleaving parallelism.

Example. Figure 4 shows an initial comprehensive specification of the coffee machine. The fragment $F$ is composed by the store $S$ and the concatenation of two processes, namely $D$, which specifies an initial design phase, and $R$, which specifies the run-time behaviour of the coffee machine.

The store $S$ is made of two parts: some constraints derived from the requirements specification ($S_1$), and some contextual information and initial configurations ($S_2$).

The design process $D$ is quite simple. It is just formed by the parallel composition of the installation of some of the features that the coffee machine may exhibit. This specifies a sort of race between features and may be thought of as independent designers competing to install the features they are responsible for. The semantics of FLAN ensures that all executions will end up with a consistent configuration if the process begins with a consistent store. For instance, the semantics will forbid the installation of mutually exclusive features.

Process $R$ describes the run-time operation of the coffee machine. Depending on the country it is meant for, the machine may either accept a euro or a dollar. After that, it may be subject to a sugar regulation ($P_2$) or not ($P_3$). The next step is the beverage selection and delivery, which may be followed by a ringtone ($P_4$) or not, after which it returns to its initial state.

$F \doteq [S \parallel D; R]$

$S \doteq S_1 \otimes S_2$
$S_1 \doteq \text{has(euro)} \lor \text{has(dollar)}$
$\text{in(Europe)} \rightarrow \text{has(euro)}$
$\text{in(Canada)} \rightarrow \text{has(dollar)}$
$\text{has(coffee)} \lor \text{has(cappuccino)} \lor \text{has(tea)}$
$\text{has(tea)} \rightarrow \text{in(Europe)}$
$\text{dollar} \otimes \text{euro}$
$\text{cappuccino} \rightarrow \text{has(cappuccino)}$
$\text{do(euro)} \rightarrow \text{has(euro)}$
$\text{do(dollar)} \rightarrow \text{has(dollar)}$
$\text{do(sugar)} \rightarrow \text{has(sugar)}$
$\text{do(coffee)} \rightarrow \text{has(coffee)}$
$\text{do(cappuccino)} \rightarrow \text{has(cappuccino)}$
$\text{do(tea)} \rightarrow \text{has(tea)}$
$\text{do(ringtone)} \rightarrow \text{has(ringtone)}$
$S_2 \doteq \text{in(Europe)}$
$\text{has(euro)}$
$\text{has(dollar)}$
$D \doteq \text{install(sugar).0 \mid install(coffee).0 \mid install(tea).0}$
$\mid \text{install(cappuccino).0}$
$R \doteq (\text{ask(in(Europe)).euro.0}$
$+ \text{ask(in(Canada)).dollar.0}) \cdot (P_2 + P_3)$
$P_2 \doteq \text{sugar.P}_1$
$P_3 \doteq \text{coffee.P}_4 \lor \text{tea.P}_4 \lor \text{cappuccino.P}_5$
$P_4 \doteq P_3 \lor R$
$P_5 \doteq \text{install(ringtone).ringtone.R}$

Figure 5: Final specification of the coffee machine

$F' \doteq [S' \parallel D'; R']$

$S' \doteq S_1 \otimes S_2'$
$S_2' \doteq \text{in(Europe)}$
$D' \doteq \text{install(euro).0 \mid install(dollar).0}$
$\mid \text{install(sugar).0 \mid install(coffee).0 \mid install(tea).0}$
$\mid \text{install(cappuccino).0}$
$R' \doteq (\text{euro.0 + dollar.0}) \cdot (P_2 + P_3)$

4. MAUDE: AUTOMATED ANALYSES

In this section we describe some automated analysis activities supported by the implementation of our approach in Maude’s formal environment.

We illustrate the use of some of the tools in what could be a typical specification and analysis life-cycle of a product family within our framework: (i) an initial constraint store (capturing the feature constraints described in the requirements) is specified and checked for consistency; (ii) a design process is specified and executed step-by-step; (iii) a consistency check is performed on all possible configurations allowed by the design process; and (iv) the product behaviour is specified and checked with respect to its requirements (that may include temporal requirements in addition to features constraints). We underline that this is only an example. The tools and techniques we illustrate can be combined and applied in many other ways.

Checking the consistency of the initial constraints. The consistency of a store is implemented by a function consistent that, given a constraint store, returns true if the store is consistent and false otherwise. This function can be used to check, e.g., the consistency of the initial store $S$ presented in Fig. 4 as follows.

Maude> red in ANALYSIS-KRIPKE : inconsistency(S) .
...
result neConstraints: has(dollar) has(euro) dollar * euro

The analysis spots the inconsistency of assuming the presence of two mutually excluding features (the euro and dollar coin slots) by reporting the subset of constraints formed by has(dollar), has(euro) and dollar * euro. There were,

Maude uses * to denote $\otimes$.  

2
of course others, like the presence of both has(dollar) and in(Europe) forbidden by in(Europe) → has(euro).

We can fix this issue and produce a new initial store S′ (cf. Fig. 4) in which the installation of euro and dollar is delegated to the new design process D′, cf install(euro).0 and install(dollar).0. Indeed, the latter will not be executed, since it would make the store inconsistent.

We can verify the consistency of S′ as follows:

Maude> red in ANALYSIS-KRIPKE : consistent(S′) .
... result Bool: true

The result confirms that the initial store S′ is consistent.

Executing the design process. Starting from a consistent store, the user may want to specify and execute a design process that ends up with a maximally configured product. Consider for instance the initial store S′ and the new design process D′ presented in Fig. 4.

The Maude command rew can be used to execute the fragment [ S′ | D′ ] as follows.

rewrite in ANALYSIS-KRIPKE : ! [ S′ | D′ ] .
... result KFragment: ! [ has(dollar) has(coffee) has(tea) has(cappuccino) has(sugar) ... | 0]

The fragment runs until the underlying process becomes the empty process resulting in a product configured with several features (for reading purposes, the part of the store that has not changed is abbreviated with ...). Clearly, such a configuration is ensured to be consistent since it was derived from a consistent store.

Checking the consistency of all configurations. Of course, even if we are ensure the semantics of FLan preserves consistency we can use the reachability command reach to check consistency of all reachable configurations as follows.

search in ANALYSIS-KRIPKE : ! [ S′ | D′ ] =>* x:KFragment such that consistent(x:KFragment) == false = true .
... No solution

The absence of solutions ensures that no inconsistent configuration is reachable.

Checking behavioural properties. After fixing the specification of the design we can analyse the run-time behaviour of the product. We can now check, for instance, that the run-time behaviour does not introduce inconsistencies. We can do it as before but we can also resort to the LTL model checker of Maude. The property we check is [] isConsistent, i.e. consistency is an invariant.

Maude> red in ANALYSIS-KRIPKE : modelCheck( ( ! [ S′ | D′ ; R ] ) , [] isConsistent ) .
... result Bool: true

The result confirms that consistency is preserved during the run-time operation of the coffee machine.

We may however notice that the conditional statement used to accept a dollar or a euro is actually redundant due to the introduced constraints. A possible, simpler run-time process is R′ (cf. Fig. 5). It is very much like R, but the conditional statement has been replaced by a non-deterministic choice that will be consistently solved at run-time due to the presence of the action constraints do(euro) → has(euro) and do(dollar) → has(dollar) in the store, which will forbid the use of the actions euro or dollar if the corresponding feature has not been installed. This time, contrary to what we did earlier for the initial store and design process, we are replacing procedural information by declarative information. The resulting process enjoys the property of preserving consistency, which can be checked as follows.

Maude> red in ANALYSIS-KRIPKE : modelCheck( ( ! [ S′ | D′ ; R′ ] ) , [] isConsistent ) .
... result Bool: true

The result confirms that consistency is still preserved during the run-time operation of the coffee machine.

The LTL model checker can of course be used to check additional requirements. For instance, we can check the temporal requirement 4 of our case study (i.e. “a ringtone must be rung after serving a cappuccino”).

Maude> red in ANALYSIS-LTS : modelCheck( ( ! (do('machine')([S′ | D′ ; R′]) ) , [] (cappuccino) -> <> {ringtone} ) ) .
... result Bool: true

The result confirms that a ringtone eventually follows (the delivery of) a cappuccino.

The above example analyses illustrate how the implementation of FLAN in Maude allows us to exploit Maude’s rich analysis toolset. In this respect, it is worth noting that in the above analyses we have made use of only a limited number of Maude tools, namely its SAT solver, its reachability analyser and its LTL model checker. There are several other Maude tools whose use remains to be investigated.

5. RELATED WORK

There is an increasing body of research on how to successfully apply automated behavioural verification techniques, like model checking, in the particular context of (software) product families. The challenge, to the best of our knowledge first recognised in [22, 23], is to develop formal and modular modelling and verification approaches which specifically take cross-cutting feature constraints into account. In this section, we discuss a number of formal methods and analysis techniques that have been applied in SPL.E.

There are two well-known lines of research on modelling product families in terms of extensions of LTSs, which both define family behaviour as actions (features) and use advanced model-checking techniques for the verification of behavioural properties. One makes use of extensions of Modal Transition Systems (MTSs) [12, 18, 20, 21], the other of Featured Transition Systems (FTSs) [10].

Modal Transition Systems. MTSs [19] were recognised as a suitable behavioural model for describing product families in [12]. A fixed-point algorithm, implemented in a tool, is defined to check whether an LTS conforms to an MTS with respect to several different branching relations. In the context of SPL.E, it allows us to check the conformance of the behaviour of a product against that of its product family.
VMC (http://fmt.isti.cnr.it/vmc/) is a tool for modelling and analysing behavioural variability in product families modelled as MTSs. VMC thus accepts a product family specified as an MTS, possibly with additional variability constraints, after which it allows the user to interactively explore this MTS; efficiently model check properties (branching-time temporal logic formulae) over an MTS; visualise the (interactive) explanations of a verification result; automatically generate one, some, or all of the family's valid products (represented as LTSs); and finally, help the user to understand why a certain valid product does or does not satisfy specific verified properties, by allowing such a product to be inspected individually.

**Featured Transition Systems.** An FTS is a doubly labelled transition system with an associated feature diagram. Its states are labelled with atomic propositions, while a specific distinction among its transitions is obtained by an edge-labelling defining which transitions refer to which features.

SNIP is a model checker for product families modelled as FTSs specified in a language based on that of the SPIN model checker (http://spinroot.com). Features are declared in the Text-based Variability Language (TVL) and are taken into account by the explicit-state model-checking algorithm of SPIN for verifying properties expressed in ILTL (feature LTL) interpreted over FTSs (e.g. to verify a property over a subset of the set of all valid products). Exhaustive model-checking algorithms (which continue their search also after a violation was found) moreover allow to verify all products of a family at once and to output all of the products that violate a property. Unlike VMC, SNIP is a command-line tool without a GUI. SNIP, however, treats features as first-class citizens, with built-in support for feature diagrams, and it implements model-checking algorithms specifically tailored for product families.

In this paper, we proposed to specify product families in a high-level formal process-algebraic language, FLAN, which has transition systems as semantic domain. While, in principle, product family behaviour could be directly specified using transition systems from a practical point of view it is more convenient to resort to some more intuitive linguistic formalism. In fact, when used as a specification formalism, transition systems are too low level and, above all, suffer from the lack of compositionality—in the sense that they offer no means for constructing the transition system of a family in terms of that of its components. On the contrary, the process-algebraic linguistic terms offered by FLAN are more intuitive and concise notations. Using them, product families can be built in a compositional way.

Like the approach based on FTSs, we thus use a high-level language for modelling, treating features as first-class citizens, and a transition system semantics for analysis. While we currently use Maude for the automated verification of behavioural properties of product families specified in FLAN, in the future we hope to make their semantic models (LTSSs, basically) amenable to model checking with VMC. FLAN is loosely inspired by the CCS-like process algebra CLISP presented in [13]. Unlike FLAN, however, CLISP has no language constructs for the cross-tree constraints known from feature models nor a store of constraints to separate the declarative aspects of a product family from its procedural aspects.

**Feature-aware verification.** Tool suite SPLVERIFIER uses standard off-the-shelf model-checking techniques to verify the absence of feature interactions by means of an approach called feature-aware verification. To this aim, the AUTOFEATURE automata language for specifying features in separate and composable units was developed, while a variant of abstract syntax trees, called Feature Structure Trees (FSTs), forms the basis for encoding the variability. SPLVERIFIER offers two methods: a brute-force one generating and verifying all valid products, while an alternative one avoids the generation of all individual products as it verifies all possible feature combinations on a single product that is purpose-built to contain all the family's features. Like SNIP and FLAN, features are central to SPLVERIFIER, but only the (renowned) problem of detecting feature interactions is addressed. Unlike VMC, SNIP and FLAN, behavioural variability is not considered.

**Process-algebraic approaches.** A process-algebraic theory for the modelling and analysis of product families was developed also in [15, 16, 21]. PL-CCS extends CCS by a variant operator that allows to model alternative behaviour in the form of alternative processes, with the meaning that only one of the alternative processes will exist at run-time. PL-CCS has an SOS semantics defined over multi-valued MTSs. To reason on the behaviour of product families specified in PL-CCS, a multi-valued version of the modal µ-calculus is defined, i.e. the interpretation of a logic formula over a product family no longer yields true or false, but rather a set of configurations characterising exactly those products of the family which satisfy the behavioural property under verification. Unlike FLAN, PL-CCS however does not cater for the cross-tree constraints known from feature models. Also, the analysis is limited to verification by model checking which is moreover not implemented.

**Petri-net-based approaches.** The same idea underlying FTSs, namely to explicitly label the transitions of an LTS with the set of features (i.e. products) for which the transition is available, was also applied to Petri nets in [25, 20], resulting in feature (Petri) nets. Larger feature nets can be constructed from smaller ones to model the addition of new features to a product family, while correctness criteria can ensure that the resulting composition preserves the original behaviour. An extension can capture the dynamic reconfiguration of products by associating to each transition of a feature net also an update expression that describes how the feature selection evolves after firing (executing) the transition. The resulting feature reconfiguration model may remain disconnected from the ordinary behavioural model, thus offering orthogonality but at the same time allowing the reconfiguration to depend upon the underlying behaviour and vice versa. This has some similarities with the combination of declarative and procedural views that is at the heart of FLAN. Efficient formal analysis and verification techniques from Petri nets of course become available to feature nets, but their application in the specific context of product families has not yet been studied.

In [30], FTSs are translated into so-called adaptable featured Petri nets, after which projection and reachability analysis is performed over the resulting Petri net.
techniques from Petri nets become available for product derivation and liveness analysis.

**Other approaches.** In [17], FTSs (including their associated feature diagrams) are translated into Maude specifications by graph transformation. Starting from a set of requirements, this means that first a feature diagram needs to be extracted (to model the variability) and only then the desired run-time behaviour can be specified (as an FTS). FLAN, on the contrary, allows to combine the specification of design and run-time processes directly from a given set of requirements, which may be very convenient, for instance to specify the behaviour of partially configured or run-time configurable products. Another difference is that the semantic foundation of our approach is based on techniques from concurrent constraint programming and process algebras rather than graph transformation.

In [14], a feature-oriented approach to modelling product families in Event-B by means of a chain of refinements is explored by applying existing Event-B (de)composition techniques to two case studies, using a prototypical feature composition tool. Behavioural variability is not considered, but it would be interesting to explore the feasibility of using this Feature Event-B as a high-level specification language on top of one of the aforementioned semantic models.

### 6. CONCLUDING REMARKS

We have introduced the feature-oriented language FLAN as a proof of concept for specifying and analysing both declarative and procedural aspects of product families.

We do not envisage FLAN to become the feature-oriented language, but we advocate that some of its features are very convenient and may be adopted by existing languages.

First, we think that the concurrent constraint programming paradigm provides a flexible mechanism for separating and (when necessary) combining declarative and procedural aspects. For instance, design decisions can be delayed until run-time, which is very convenient for software product families where features may be added while the system operates. Furthermore, the run-time specification can be discharged from design decisions such as feature constraints thus resulting in light-weight, understandable specifications.

Second, the implementation of FLAN in Maude allows one to exploit the rich analysis toolset of this framework. In this paper, we have essentially restricted ourselves to its SAT solver, its reachability analyser and its LTL model checker. However, there are other Maude tools whose use may be worth investigating. The statistical model checker PVeSta, for instance, could be used for evaluating the performance of product families in variants of FLAN with stochastic and quantitative aspects.

### 7. FUTURE WORK

We envisage several potentially interesting extensions of FLAN. For one, we can adopt further primitives and mechanisms from the concurrent constraint programming tradition. The concurrent constraint λ-calculus [8], for instance, provides synchronisation mechanisms typical of mobile calculi (i.e. name passing), a check operation to prevent inconsistencies, a retract operation to remove (syntactically present) constraints from the store and a general framework for soft constraints (i.e. not only boolean). Such features have been shown successful for the specification of service level agreements and negotiation processes [7]. This may thus turn out to be useful when product families are to be designed by cooperating partners and are hence subject to negotiation mechanisms.

Another promising line of research is to provide an FTS and an MTS semantics of FLAN so that (i) FLAN becomes a high-level language for those semantic models and (ii) we can exploit the specialised analysis tools developed for them.

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### 9. REFERENCES


APPENDIX
Implementation

This section documents the complete specification of our implementation of FLAN in Maude.

```
load model-checker.maude.

fmod FLAN-FEATURES is
  inc QID.
  including SATISFACTION.

  sort Feature.
  subsort Qid < Feature. --- We use quoted identifiers as features

  --- Actions
  sorts Action InstallAction OtherAction.
  subsort InstallAction OtherAction < Action.
  subsort Feature < OtherAction. --- Let us use features as actions

  op install : Feature -> InstallAction.
  op ask : Prop -> InstallAction.
  op do : Action -> Prop. --- Predicate stating that fragment does an action
  op has : Feature -> Prop. --- Predicate stating that fragment has the feature

endfm

fmod FLAN-CONSTRAINTS is

  pr FLAN-FEATURES.
  pr SAT-SOLVER.

  sorts Constraint Constraints neConstraints.
  subsort Constraint < neConstraints < Constraints.
  subsort Formula Prop < Constraint.

  --- Constraints over features
  op _ * _ : Feature Feature -> Prop [ctor comm].
  op _ |> _ : Feature Feature -> Prop.

  --- Constraints set operators
  op _ _ : neConstraints Constraints -> neConstraints [assoc comm].
  op _ _ : Constraints neConstraints -> Constraints [assoc comm].
  op _ _ : Constraints Constraints -> Constraints [assoc comm].

  vars Cons Cons' : Constraints.
  vars neCons : neConstraints.
  vars cl c1 c2 : Constraint.
  vars f g : Feature.
  vars formula1 : Formula.
  vars oal : OtherAction.

  --- Id of set union
  eq neCons True = neCons.

  --- Idempotency of set union
  eq neCons neCons = neCons.

  --- Some basic entailment reductions
  --- Since entailment is expensive, we declare the operator as "memo" to memoize results.
  op _ |= _ : Constraints Constraint -> Bool [memo].

  --- Some trivial cases
  eq (neCons cl |= cl) = true.
  eq (cl |= cl) = true.
  eq (neCons ('c' cl) |= cl) = false.
  eq ('c' cl) |= cl = false.

  --- Entailment via SAT
  ceq (Cons |= cl) = true

if (satSolve(store2sat(Cons) \ " cl) == false).
  --- Default case
  eq (Cons |= cl) = false [otherwise].

  --- A procedure for checking some local inconsistencies
  op check : Constraints Constraint -> Bool.
  eq check(True, cl) = true.
  eq check(Cons, has(f)) = false.
  eq check(Cons = has(f)) = true [otherwise].

  --- Checking of for installation of new features
  --- wrt. to "exclude" constraints only
  eq check(('f' * g) has(f) Cons, has(f)) = false.
  eq check(('f' * g) has(f) = has(g)) = true.

  --- Checking all other actions (wrt. to explicit
  --- constraints of the form oal -> ...)
  ceq check(Cons (' do(oal)') \" formula1), do(oal))
    = true.
  eq check(Cons, (do(oal)) \" formula1), do(oal))
    = false.

  --- A procedure to check consistency with respect
  --- to feature constraints

  --- Other boolean inconsistencies are ignored (assumed to not exist)
  op consistent : Constraints -> Bool.
  eq consistent(Cons) = (inconsistency(Cons) == True).

  --- A simple procedure to check and find cross-tree
  --- feature inconsistencies
  --- Other boolean inconsistencies are ignored (assumed to not exist)
  op inconsistency : Constraints -> Constraints.
  eq inconsistency(C1) = True.
  eq inconsistency((f * g) has(f) has(g) Cons) = ((f * g) has(f) has(g)).
  eq inconsistency((f * g) has(f) has(g)) = ((f * g) has(f) has(g)).
  ceq inconsistency((f |> g) has(f) Cons) = ((f |> g) has(f)).
  eq inconsistency((f |> g) Cons) = inconsistency(Cons).
  eq inconsistency((f |> g) has(f)) = inconsistency(has(f)).
  eq inconsistency((f |> g) has(f) Cons) = ((f |> g) has(f)).
  eq inconsistency((f |> g) has(f) = has(g)).

  --- Simplifications
  eq inconsistency((f |> g) has(f) Cons) = inconsistency(has(g) Cons).
  eq inconsistency((f |> g) has(g) Cons) = inconsistency(has(f) Cons).
  eq inconsistency((f |> g) Cons) = inconsistency(Cons).

  --- Default case true (all inconsistencies captured above)
  eq inconsistency(Cons) = True [otherwise].

  --- A full consistency procedure (not only feature
  --- inconsistencies)
  op fully-consistent : Constraints -> Bool.
  --- We reduce the problem to SAT and use Maude's SAT solver
  eq fully-consistent(Cons) = (satSolve(store2sat(Cons)) \" false).

  --- This function essentially replaces constraint
  union with boolean conjunction
  op store2sat : Constraints -> Formula.
  eq store2sat(True) = True.
  eq store2sat(False) = False.
  eq store2sat(('f' * g) = has(f) \" has(g)).
  eq store2sat(('f' * g) = has(f) \" has(g)).
  eq store2sat(cl) = cl.
  eq store2sat(neConsCons) = cons /\ store2sat(neCons).

endfm

fmod FLAN-SYNTAX is
inc FLAN-CONSTRAINTS.
```
--- Fragments
sort Fragment . --- Syntactic category FT in Fig. 1

--- Processes
sort Process .

sort ProcessId . --- Vocabulary A in Fig. 1
subsorts Qid < ProcessId . --- Fragment ids are quoted identifiers.
subsort ProcessId < Process . --- Process Ids are processes

--- Some structural axioms (idempotency and identity are handled with equations)
vars P Q : Process.
vars K : Prop.
op 0 : -> Process [ctor].
op _ ; _ : Process Process -> Process [ctor frozen prec 10 gather (e E)].
op _ + _ : Process Process -> Process [assoc comm frozen prec 20 gather (E e)].
op _ | _ : Process Process -> Process [assoc comm frozen prec 20 gather (E e)].

--- Derived operators
op if _ then _ else _ fi : Formula Process Process -> Process [ctor frozen prec 15 gather (E E E)].
eq if K then P else Q fi = (ask (K) . P) + (ask (~ K) . Q).
eq P + 0 = P.
eq P + P = P.
eq P ; 0 = P.
eq 0 ; P = P.
eq P | 0 = P.

--- transitions
mod FLAN-SEMANTICS is
pr FLAN-SYNTAX.
pr FLAN-RECURSION.

--- The implementation of the SOS semantics follows
--- the Verdejo&Oliet approach
--- Labelled fragments are used to encode labelled transitions
sort LabelledFragment.
sort Fragment < Process.
subsort Fragment < ProcessId.

--- Labelling operator
sort Label.
sort Action < Label. --- Just use actions as labels
vars f : Feature.
vars act1 : Feature.
vars a b c : Label.
vars P P' Q Q' : Process.
vars LabF LabF' : LabelledFragment.
vars K : Prop.
vars PId1 PId2 : ProcessId.
vars oa1 : OtherAction.

--- Rule Install in Fig. 2
crl [Install] : [Cons | install (f) . P] => {install(f)} [Cons | P]
if consistent (Cons has (f)) /
   Cons' := Cons has (f).

--- Rule Act in Fig. 2
crl [Act] : [Cons | ask (K) . P] => {ask} [Cons | P]
if Cons |= K.

--- Rule Or in Fig. 2
crl [Or] : [Cons | (P + Q)] => {a} [Cons' | P']
if [Cons | P] => {a} [Cons' | P'].

--- Rule Seq in Fig. 2
crl [Seq] : [Cons | (P ; Q)] => {a} [Cons' | (P' ; Q)]
if [Cons | P] => {a} [Cons' | P'].

--- Rule Par in Fig. 2
crl [Par] : [Cons | (P | Q)] => {a} [Cons' | (P' | Q']
if [Cons | P] => {a} [Cons' | P'].

--- This is only a test.
crl [ParC] : [Cons | (P | Q)] => {install(f)} [Cons' | (P' | Q')]
if [Cons | P] => {install(f)} [Cons' | P'] \
   [Cons | Q] => {install(g)} [Cons'' | Q']

--- Auxiliary rules to expand definitions when needed
crl [def] : [Cons | PId1] => {a} [Cons' | P]
if PId1 definedIn specification
   [Cons | def(PId1, specification)] => {a} [Cons' | P].
--- A function to check the consistency of a Fragment
op consistent : LabelledFragment -> Bool .

subsort KFragment < State .

vars F : Fragment .

op isConsistent : -> Prop .

vars F : Fragment .

eq ! F |= isConsistent = consistent(! F) .

--- A function to check the consistency of a Fragment
op consistent : TracedFragment -> Bool .

vars a b c : Label .

vars F : Fragment .

eq consistent(! F) = consistent(F) .

--- A function to check the consistency of a Fragment
op consistent : KFragment -> Bool .

vars a b c : Label .

vars F : Fragment .

eq consistent(F) = consistent(! F) .

--- A function to check the consistency of a Fragment
op consistent : Region -> Prop .

vars r r' : Region .

op isConsistent : -> Prop .

vars r : Region .

eq ! r |= isConsistent = consistent(! r) .

--- A function to check the consistency of a Fragment
op consistent : Product -> Bool .

vars a b c : Product .

op isConsistent : -> Prop .

vars a : Product .

eq ! a |= isConsistent = consistent(! a) .

--- A function to check the consistency of a Fragment
op consistent : Currency -> Prop .

vars a b c : Currency .

op isConsistent : -> Prop .

vars a : Currency .

eq ! a |= isConsistent = consistent(! a) .

--- A function to check the consistency of a Fragment
op consistent : Feature -> Prop .

vars a b c : Feature .

op isConsistent : -> Prop .

vars a : Feature .

eq ! a |= isConsistent = consistent(! a) .

--- A function to check the consistency of a Fragment
op consistent : Feature -> Prop .

vars a b c : Feature .

op isConsistent : -> Prop .

vars a : Feature .

eq ! a |= isConsistent = consistent(! a) .
--- euro, exclusively for products for the European market
( in(Europe) -> has(euro) )
--- dollar, exclusively for Canadian products
( in(Canada) -> has(dollar) )
--- every product must offer at least one beverage
( has(coffee) V has(cappuccino) V has(tea) )
--- tea may be offered only by European product
( has(tea) -> in(Europe) )
--- all products that offer cappuccino must also offer coffee
( cappuccino | coffee )
--- standard do(feature) -> has(feature)
( do(euro) -> has(euro) )
( do(dollar) -> has(dollar) )
( do(sugar) -> has(sugar) )
( do(coffee) -> has(coffee) )
( do(cappuccino) -> has(cappuccino) )
( do(tea) -> has(tea) )
( do(ringtone) -> has(ringtone) )

--- Commands exemplified in the paper
--- red in ANALYSIS-KRIPKE : consistent(S).
--- red in ANALYSIS-KRIPKE : inconsistencies(S).
--- rew in ANALYSIS-KRIPKE : ! [ S' | D' ]
--- search [1] in ANALYSIS-KRIPKE : ![ [ S' | D' ] => x:KFragment such that consistent(x:KFragment) = false
--- red in ANALYSIS-KRIPKE : modelCheck( ![ S' | D' ],([], isConsistent) ).
--- red in ANALYSIS-KRIPKE : modelCheck( ![ S' | D' ],([], isConsistent) ).
--- red in ANALYSIS-LTS : modelCheck( ![ S' | D' ]+[S' | D' ; R' ]+[Cappuccino] -> <> (ringtone) ) .

--- some contextual information
eq S2 = ( in(Europe) ) ( ~ in(Canada) )
( has(euro) )
( has(dollar) ).

ops D D' R R' P1 P2 P3 P4 P5 : -> Process.
eq D = install(sugar) . 0 | install(coffee) . 0 | install(tea) . 0 | install(cappuccino) . 0 | install(euro) . 0 | install(dollar) . 0.
eq D' = install(sugar) . 0 | install(coffee) . 0 | install(tea) . 0 | install(cappuccino) . 0 | ( ask(in(Europe)) . install(euro) . 0 ) + ( ask(in(Canada)) . install(dollar) . 0 ).
eq R = ( ( ask(in(Europe)) . euro . 0 ) + ( ask(in(Canada)) . dollar . 0 ) ) ; 'P2 .
eq R' = ( euro . 'P2 ) + ( dollar . 'P2 ) .
eq P2 = sugar . 'P3 .
eq P3 = ( coffee . 'P4 ) + ( tea . 'P4 ) + ( cappuccino . 'P5 ) .
eq P4 = 'P5 + 'R .
eq P5 = install(ringtone) . ringtone . 'R .
eq specification = ( 'D = def D )
( 'D' = def D' )
( 'R = def R )
( 'R' = def R' )
( 'P1 = def P1 )
( 'P2 = def P2 )
( 'P3 = def P3 )
( 'P4 = def P4 )
( 'P5 = def P5 ) .

endm

mod ANALYSIS-KRIPKE is
pr FLAN-COFFEE-MACHINE .
pr FLAN-KRIPKE-CHECK .
endm

mod ANALYSIS-LTS is
pr FLAN-COFFEE-MACHINE .
pr FLAN-LTS-CHECK .