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Covering SPL Behaviour with Sampled Configurations: An Initial Assessment

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ABSTRACT

Structural approaches to Software Product Lines (SPL) testing (such as pairwise testing) have gained momentum as they are able to scale to larger SPLs described as feature diagrams (FD). However, these methods are agnostic with respect to behaviour: the sampled configurations have thus no reason to satisfy any given behavioural criterion. In this paper, we investigate the behavioural coverage of two structural testing criteria: pairwise and similarity. To do so, we modelled four SPLs in terms of feature diagrams and associated featured transitions systems (FTSs). We then computed state, action and transition coverage for a set of generated configurations. Preliminary results indicate that for relatively small variability models with few cross-tree constraints, structural coverage-driven tools tend to cover large parts of behaviour with less than 8 configurations. Though structural coverage cannot be used directly as a replacement for behavioural driven SPL test generation, opportunities to mix structural and behavioural coverage for efficient and effective SPL testing do exist.

Categories and Subject Descriptors

D.2.5 [**Software Engineering**]: Testing and Debugging; D.2.13 [**Software Engineering**]: Reusable Software

General Terms

Reliability, Verification, Algorithms, Measurement

Keywords

SPL Testing, Structural Coverage, Featured Transition System

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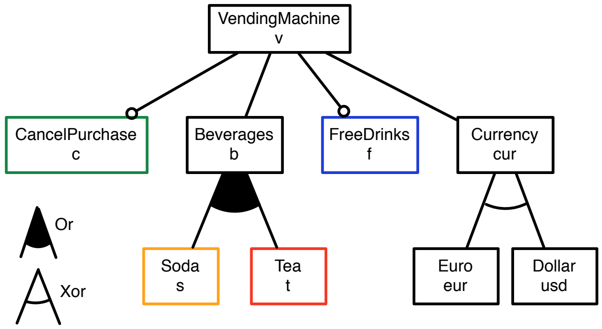
1. INTRODUCTION

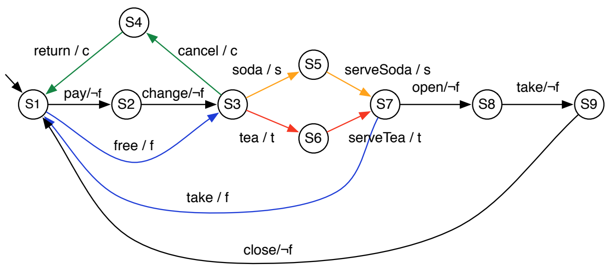
Software Product Line (SPL) testing is an intrinsically difficult activity [30]. One of the main challenges is the combinatorial explosion of the number of products to be tested. To bypass this explosion, sampling techniques have been defined to select configurations of interest from a Feature Diagram (FD). These techniques involve the definition of structural coverage criteria on the FD, such as t-wise coverage [6, 11, 20, 33] where the set of sampled products must contain all combinations of t features, or more recently similarity testing [15], where the goal is to select products that are as different as possible. These methods became attractive because they usually produce small numbers of configurations to test, scale up to thousands of features [15, 20], have demonstrated their bug-finding abilities on real cases such as Eclipse [21] or automotive systems [36] and are being integrated in popular feature modelling environments, such as FeatureIDE or Pure::Variants. Additionally, they can be combined with other criteria (such as the cost of testing or the maximum number of products to consider) acknowledging the multi-objective nature of a testing budget [17, 22]. Such approaches do not take SPL behaviour into account. In contrast, variability-aware testing [23] embraces the whole SPL code to perform test case generation. At the model level, there is a growing body of work on behavioural SPL coverage [2, 7–10]. Yet these criteria may be expensive to compute on large SPLs. Thus, we formulate a simple research question:

Practically, which behavioural coverage similarity and pairwise sampling do achieve?

To address this question, we modelled four SPLs mixing "academic" examples and real cases: each is composed of a behavioural model (given in terms of FTS) and its related FD. We then applied t-wise [20] and similarity [15] techniques to extract a set of configurations. By projecting the FTS for each selected configuration, we get a transition system from which it is possible to compute the coverage of the FTS representing the whole SPL. Preliminary results indicate that full coverage of states, transitions and actions can indeed be achieved with few configurations (no more than 3) and that 3-wise sampling worked best in these cases. Similarity worked better than t-wise for $t = \{1, 2\}$, although a detailed comparison is beyond the scope of this paper.



(a) Feature Diagram (FD)



(b) Featured Transition System (FTS)

Figure 1: The soda vending machine example [4]

All these samplings obtain full coverage with more products than needed. In [10], we proposed a dedicated behavioural heuristic requiring less configurations to compute all-states coverage on our larger model. We therefore see potential for mixing structural/behavioural coverage rather than systematically considering them in isolation.

The rest of this research in progress contribution is structured as follows: Section 2 introduces structural and behavioural coverage-driven test case generation for SPLs. Section 3 presents our experimental set-up and results obtained so far and Section 4 provides initial insights into these results. Section 5 covers related works while Section 6 concludes the paper.

2. BACKGROUND

We focus on model-based testing of SPLs [29,32]. In this context, roughly two categories of approaches can be considered: *structural* approaches, which samples configurations of interest from the FD only, and *behavioural* approaches that uses behavioural models (e.g. state machines, transition systems, automata, sequence diagrams) to generate test cases.

2.1 Structural SPL Testing

To tackle the combinatorial explosion of the number of configurations to consider for a given FD, sampling techniques have been proposed. They rely on the satisfaction or maximisation of a criteria. Here, we consider t-wise feature coverage and (dis)similarity.

2.1.1 T-Wise Coverage

Combinatorial Interaction Testing (CIT) [5,24,39] is a relevant approach to reduce the number of products for testing. CIT techniques sample large domains of test data. It is based on the observation that most of the faults are triggered by the interactions between a small number of features [24]. An interaction between t features denotes the possible impact of one functionality on the others. Kuhn *et al.* [24] have shown that covering all interactions between two features are able to disclose 80% of the bugs. In some cases, higher interaction strengths may be needed [25]. Considering all possible interactions between t features is called t-wise coverage. Such approaches have been adapted to SPL testing [19, 31, 33], generating configurations from the FD covering all the valid 2-wise combinations of features. Some of them, like [19], also consider higher values of t. Generally, no more than few dozens configurations are necessary for pairwise coverage.

However, computing all the t-wise interactions in the presence of constraints, as it is the case for FDs, is NP-complete in the general case [19,34]. As a result, although t-wise generation techniques from FDs have greatly improved, now relying on efficient satisfiability (SAT) solvers [20], higher interaction strengths ($t > 2$) may remain inaccessible for large FDs. This is particularly problematic since 3-wise interactions were shown to commonly appear in SPL testing practice [36].

2.1.2 Similarity-Based SPL Testing

In model-based testing, it has been found that test suites containing dissimilar test cases have a higher fault detection power than similar ones [12,13]. At the FD level, it means that a set of configurations that have few selected/unselected features in common is more likely to find faults (through associated test cases) than a configuration set that has more commonalities in feature choices. This hypothesis has been empirically validated [16]. To select such dissimilar configurations, we rely on a distance function. The advantage over explicit t-wise coverage, is that the function is easy to compute, allowing to scale easily to large FDs while still achieving a decent t-wise coverage even for high interaction strengths (t=6). Henard et al. proposed a search-based technique for selecting and prioritising configurations according to a similarity heuristic [15] for large FDs. Subsequently, Al-Hajjaji et al. followed this direction [1], suggesting that similarity testing has appeal even for smaller FDs.

2.2 Behavioural Coverage Driven Testing

In our previous work [7–10], we defined and partially implemented an approach to generate test cases from a behavioural model of the SPL. In particular, we defined the notion of test case for a SPL as a sequence of actions to perform on a valid product of the SPL [9, 10]. Let us call such test case a *behavioural test case* to differentiate them from *configurations* (products) to test in t-wise coverage and similarity-based driven approaches. Behavioural test cases are selected from Featured Transition Systems (FTSs), a mathematical and compact representation of the behaviour of a SPL [4]. FTSs are Transition Systems where transitions have been labelled with feature expressions defining which products may fire the transition. For instance Fig. 1 presents the FTS of a soda vending machine with its FD. If we consider the transition $s_3 \xrightarrow{cancel/c} s_4$, only products that do have the $CancelPurchase$ feature (abbreviated as c) may abort a transaction and return money. A behavioural test case in the soda vending machine corresponds to a sequence

Table 1: Models characteristics

Model	St.	Trans.	Act.	Feat.	Prod.
Soda V. M.	9	12	13	9	24
Minepump	25	41	23	9	32
Aero UC5	25	46	12	25	256
Claroline	106	2055	106	44	5.406.720

of actions in the FTS of Fig. 1: e.g., ($free$, tea, $serveTea$, $take$). We make the distinction between executable and non-executable behavioural test cases, i.e., behavioural test cases that may be executed by at least one valid product of the product line or not.

Using those notions, we re-defined classical TS coverage criteria for FTSs as a function giving for a set of executable test cases and a FTS, a value between 0.0 and 1.0 giving the coverage percentage of the set over the FTS [10]. All-states, all-transitions, all-transition-pairs, and all-path criteria states that (resp.) all states, all transitions, all incoming/outgoing transitions for each state, and all paths in the FTS have to be covered (to read a coverage of 1.0) when executing the set of executable test-cases. The executable test cases selection problem may be seen as an optimization problem where the coverage has to be maximized and either the number of executable test cases or the number of products needed to execute all the test cases has to be minimized according to the wish of the test engineer. In a first implementation, we designed an algorithm to select a set of executable behavioural test cases that cover all states (i.e., when executing all the test cases of the set, all states are visited at least once) and executed it on different FTSs.

3. SET-UP AND RESULTS

To assess behavioural coverage of structural criteria, we consider 4 models[1] presented in Tab. 1: the Soda Vending Machine is presented in Fig. 1; the Minepump model has been presented by Classen et al. [3], it models the behaviour of a SPL of pumps for a mine that has to be kept safe from flooding and avoid explosions; we adapted the Aero UC5 model from Samih et al. [35], a Sferion™'s industrial situational awareness suite for helicopters flying in degraded visual environments, to the FTS formalism; we adapted the Claroline model, representing the navigational usages of a local instance of this online course management platform, presented in our previous work [8], to the FTS formalism. Regarding t-wise generation, we elicited the SPLCAT tool [20] for its performance [15] and PLEDGE [18] for similarity testing.

Behaviour of the different models is represented using FTSs. To measure the behavioural coverage and respond to the research question of section 1, we used state, transition and action coverage for each product selected using the different structural criteria.

3.1 Set-up

To perform our assessment, we carried out the following steps for each model and each tool (SPLCAT and PLEDGE):

1. Generate a set of configurations from the FD using each tool.

[1]All models may be downloaded from `https://projects.info.unamur.be/vibes/`.

Table 2: SPLCAT and PLEDGE parameters

Model	SPLCAT	PLEDGE		Nb. Config.
	t	x	d	
Soda V. M.	1	3	30 sec.	3
	2	6	30 sec.	6
	3	14	30 sec.	14
Minepump	1	2	30 sec.	2
	2	7	30 sec.	7
	3	13	30 sec.	13
Aero UC5	1	2	60 sec.	2
	2	8	60 sec.	8
	3	15	60 sec.	15
Claroline	1	6	60 sec.	6
	2	21	60 sec.	21
	3	71	60 sec.	71

2. Project the FTS model fts on each configuration c, to get the behavioural model (Transition System) ts corresponding to c. The projection operator for FTSs has been defined by Classen et al. [4]. It creates a new transition system ts from fts by removing all transitions that may not be executed by c, all states that may not be reached in c, and all actions that are never executed in c. Feature expressions are dropped during the process to give a behavioural model ts for c without any variability information. For instance, the projection of the configuration $\{VendingMachine$, $Beverages$, $Soda$, Tea, $Currency$, $Euro\}$ on the FTS fts in Fig. 1b will give a transition system corresponding to fts with no feature expressions on the transitions, without: states 2 and 4; their incoming and outgoing transitions; transition $s_4 \xrightarrow{take} s_1$; and pay, change, return, and cancel actions.

3. For each configuration, compute the coverage of its ts on fts: divide the number of states, transitions, and actions in ts by the number of states, transitions, and actions (resp.) in fts. The cumulated coverage is calculated by dividing the number of states, transitions, and actions in the union of the configurations' ts by the number of states, transitions, and actions (resp.) in fts. The states, transitions, and actions appearing more than once in the different configurations' ts are thus counted only once.

The FD of each model has been used as input to the SPLCAT and PLEDGE tools to generate sets of configurations. The SPLCAT tool can generate, for a given FD and a given t between 1 and 3, a set of valid configurations satisfying the 1-wise, 2-wise, or 3-wise FD coverage criteria. The PLEDGE tool can generate, for a given FD and a given number of configurations x, a certain time d, a set of x configurations using an evolutionary algorithm maximising the distance amongst configurations of the set. We used as x the number of configurations generated by SPLCAT for each model. The d parameter has the default value 60 sec., except for smaller models where it had (after several trials) to be reduced to 30 sec. to avoid memory errors during execution. Table 2 presents the different parameters used for each model and the number of generated configurations. We ran the tools on a Ubuntu Linux machine with an Intel Core i3 (3.10GHz) processor and 4GB of memory.

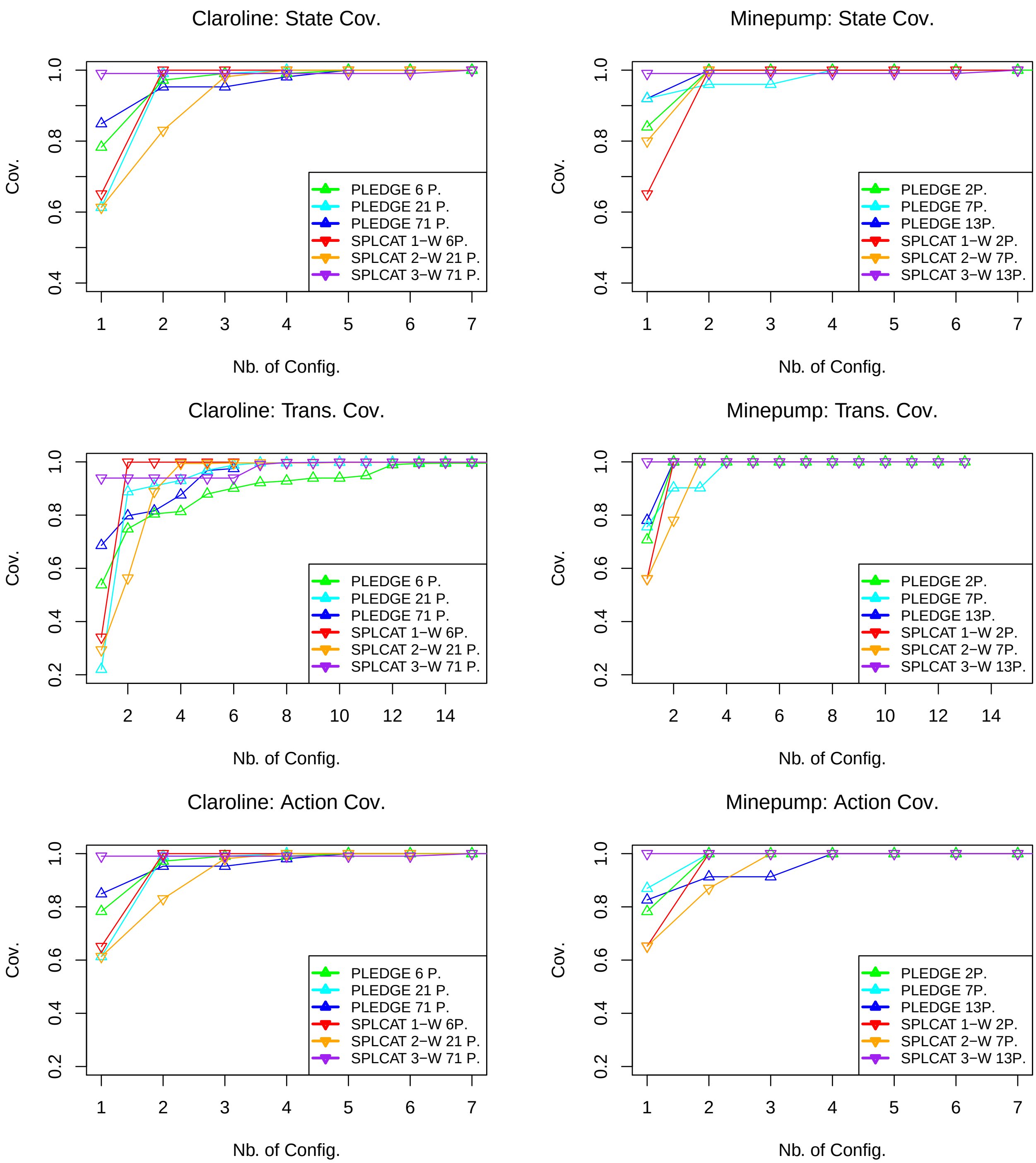


Figure 2: Model coverage of the Claroline and Minepump models

3.2 Results

We present here only results for the Claroline and Minepump models – the most representative – in Fig. 2[2]. The plots in Fig. 2 presents the cumulated coverage for states, transitions, and actions in the FTS for the different configura-

[2]Complete results may be downloaded from `https://projects.info.unamur.be/vibes/behavioural-cov.html`

tions generated using PLEDGE and SPLCAT for the Claroline and Minepump models, added progressively by order of coverage. Results for the Soda Vending Machine exhibit the same tendencies as those of the Minepump model. The Aero UC5 behavioural model has a coverage of 100% for states, transitions, and actions for every configuration generated using SPLCAT and PLEDGE, because its FTS has only 4 transitions specific to 2 different features, 2 transitions for each feature, present in each configuration. The number of configurations considered on the axis of Fig. 2 has been limited to 7 for states and actions and 14 for transitions. The number of generated configurations is higher (as shown in Tab. 2), but the cumulated coverage value did not increase further after 7 configurations for states and actions coverage and 14 configurations for transitions coverage.

4. INITIAL INSIGHTS

Regarding our research question, for the models we elaborated and settings we experimented, we obtained rapidly a complete coverage: relatively few configurations are needed to fully cover states, transitions and actions for the two approaches reported here. This is to be expected for our two "academic" models, but on larger and more realistic models (Claroline), this tendency tends to be confirmed. Of course, we need to replicate our assessment on a larger sample of realistic behavioural models, but this seems encouraging for the usage of structural coverage criteria at the FD level beyond the scope of detecting behavioural feature interactions [2].

Second, on these "small" feature models, exact t-wise coverage (SPLCAT) yielded better coverage on all our behavioural criteria for $t = 3$. This further indicates that higher values than the usual 2-wise are relevant [36] and therefore should be used when the number of configurations is "reasonable". PLEDGE tends to outperform SPLCAT on 1-wise (each feature is covered at least once) and 2-wise with a smaller number of configurations. Since for a given execution time, a smaller number of configurations means more time to evolve the population (set of configurations) and less time spent computing distances amongst them, maybe the poor performance of PLEDGE for t=3 (largest number of configurations) can be explained in such a way. We also used the local maximum distance (termed "greedy" in the tool),which is outperformed in terms of coverage by the global maximum distance (termed "NearOptimal" in the tool) [15]. It also seems that some of the memory errors we ran into (related to thread creation) can be accounted by this default choice of the algorithm. Indeed, threads are associated to evolutions of the population and local distance algorithm is fast: we therefore have a thread explosion problem on these "small" FDs. Therefore, additional settings and trade-offs need to be investigated to be able to compare the tools. Detailed tool comparison in this context is beyond the scope of our research question. This is therefore left for future work.

Finally, for both approaches, this initial assessment shows that there is also a need for prioritisation and optimal behavioural coverage. For example, on the 71 configurations generated by SPLCAT (t=3), one configuration is sufficient to cover all states on both the Minepump and Claroline models. This configuration can be found directly using our all-states algorithm [10]. If similarity and t-wise coverage are shown to consistently sample configurations that achieve good behavioural coverage, as this assessment suggests, then they can be used as first "filters" on very large feature models (assuming an intractable FTS for all-states algorithm) to prune the FTS and then run a behavioural coverage generation technique. Prioritisation may be initiated at the FTS level [8] and combined with behavioural/structural criteria [9]. There is no such one-criteria-fits-all approach in this endeavour: an all-states criterion may poorly cover transitions (e.g. on the Claroline case) [10]. Exploring synergies between these criteria, both at the structural and behavioural models, therefore seems the best option.

4.1 Threats to Validity

4.1.1 Internal Validity

Our assessment was applied on 4 models only. In order to mitigate this risk, we chose 2 "academic" models (Soda Vending machine and Minepump) and 2 larger and "real" models (AeroUC 5 and Claroline). These models were obtained from different sources and represent different kinds of systems: AeroUC5 is an embedded system where models have been designed by hand by engineers; Claroline is a web-based application where models have been reverse engineered from a running instance.

4.1.2 Construct Validity

The PLEDGE input parameters have been arbitrarily chosen. To keep a fair comparison between the results of the PLEDGE and SPLCAT tools, we kept the same number of configurations x as generated by SPLCAT. Estimating the time d, however is more tricky. In [15], we used the same generation time as SPLCAT. Unfortunately in our case, some t-wise computations did take less than 1 second in SPLCAT and PLEDGE does not allow to enter such values. Thus we initially went for the default values provided by the tool. As mentioned above, playing with a wider range of parameter values and with different similarity algorithms will mitigate this threat.

FTS models relate variability to behaviour using feature expressions on transitions, other modelling languages may relate variability to behaviour in other ways (e.g., associate variability to states instead of transitions), which will give different results for the state, transitions and actions coverage. FTS is a basic formalism to which we can easily transform other modelling languages and mappings. Thus, we can investigate the influence of the mapping between features and behavioural models.

4.1.3 External Validity

We cannot guarantee that our 4 models are representative of real SPLs. We mixed sources and domains to mitigate this threat. The largest model (Claroline) is a particular kind of application: a web application accessible through PHP pages in a web browser with a small number of states and a huge number of transitions. This kind of application allows a very flexible navigation from page to page either by clicking on the links in the different pages or by a direct access with a link in a bookmark or an e-mail. The Claroline FD has few constraints, giving a large set of possible configurations (over 5,000,000).

The small number of features in the considered FD does not allow us to generalize our results for large product lines. To the best of our knowledge, there exists no FD with both a large number of features and an associated behavioural model accessible for research and experimentation.

5. RELATED WORK

There have been few efforts to relate feature models and behavioural models to reason about both structural and behavioural coverage. Lochau *et al.* [28] create a "150%" statechart model resulting from the composition of individual behaviours associated to features. They considered coverage from a feature interaction point of view, that is when the composed machines interact through common model elements. Rather, we considered independent coverage criteria at the FM level and assessed them on 4 different SPLs.

Other approaches usually reason at only one level to assess coverage criteria for SPLs. For structural test generation, *t*-wise coverage is an obvious metric [15, 33, 39]. Regarding behavioural coverage, an initial approach [38] was to consider a product-based approach [37] and assess coverage on behavioural models where all variability has been resolved: usual model-based criteria can then be used. There is however interest in defining variability-aware versions of these criteria [9] and generation techniques [2, 27].

Finally, a promising way to evaluate coverage-driven SPL testing is mutation analysis [16, 26] paving the way for new SPL test generation techniques [14].

6. CONCLUSION

In this paper, we presented an initial assessment of SPL behavioural coverage of configurations sampled by SPLCAT (t-wise) and PLEDGE (dissimilarity-based) tools. We generated configurations for 4 models relatively small in terms of variability: from 9 up to 44 features. We showed that, for our models, the behaviour of the selected configurations covers the product line for a small set of configurations: from 3 for state and action coverage and between 5 and 8 for transition coverage. This seems promising for the usage of structural coverage criteria at the FD level. However, the formal relationship between structural and behavioural SPL coverage remains to be established. As a result, maximising behavioural coverage cannot be done only according to structural criteria. For instance, the Claroline FTS may be 100% covered using only 1 product. In our future work, we would like to establish this formal relationship to be able to define hybrid behavioural/structural criteria. The understanding of this formal relationship will also be guided by further replications of our assessment on larger and more complex (features, constraints, hard-to-reach behaviour, etc.) models.

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