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Spreadsheet-based Configuration of Families of Real-Time Specifications

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Abstract

Model checking real-time systems is complex, and requires a careful trade-off between including enough detail to be useful and not too much detail to avoid state explosion. This work exploits variability of the formal model being analysed and the requirements being checked, to facilitate the model-checking of variations of real-time specifications. This work results from the collaboration between academics and Alstom, a railway company with a concrete use-case, in the context of the VALU3S European project. The configuration of the variability of the formal specifications is described in MS Excel spreadsheets with a particular structure, making it easy to use also by developers. These spreadsheets are processed automatically by our prototype tool that generates instances and runs the model checker. We propose the extension of our previous work by exploiting analysis over valid combination of features, while preserving the simplicity of a spreadsheet-based interface with the model checker.

Spreadsheet-based Configuration of Families of Real-Time Specifications

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1 Introduction

Model checking real-time systems is complex. This particular work was motivated by and developed in collaboration with an industrial use-case provider: the Alstom railway company, in the context of the VALU3S European project. In this use-case we formally analyse a motor controller used in signalling systems: a safety-critical embedded system that reacts to instructions to turn a motor left or right. Given the criticality of this system and the need to comply to railway standards [11, 12, 13], the motor controller includes redundancy techniques, and its certification requires formal evidences that given time-bounds are met.

The implementation of this motor controller has been developed hand-in-hand with the formal specification of a real-time model in Uppaal [9], with a mutual influence between the two. Full details of this use-case can be found in our previous work [16]. The level of detail and the amount of non-determinism in early models quickly led to state-space explosions when analysing properties such as deadlock freedom. To cope with the state-space explosion problem, different details could be abstracted away. This led us to two core challenges: (i) how to efficiently involve both experts in model-checking and experts in the application domain; and (ii) how to balance trade-offs in the formal specifications between including *enough details* to be faithful to the implementation and *not too many details* to avoid model-checking more complex requirements.

Our approach involves the creation of many variations of the real-time specification, and using MS Excel spreadsheets to help keeping the developers engaged and not interacting directly with the model-checker. The Uppaal specifications are annotated, and a set of companion spreadsheets controls variability, i.e., for each variation it configures both how the annotated parts of the Uppaal specification can be modified and which requirements should be used.

Contributions. This paper presents extensions that provide a better support for variability, introducing the concept of a feature model [18] within the spreadsheets to validate configurations, and introducing integer attributes to these feature models. We provide a companion open-source tool—[Uppex](#)—that reads MS Excel spreadsheets and Uppaal models and automatizes the feature analysis and the model-checking processes. The results are validated within the railway use-case, provided by Alstom, already described in detail in our previous work [16]. We further use a simpler example that the reader can use to experiment with [Uppex](#).

Related work Model-checking complex systems is difficult and often infeasible due to space explosion. A possible approach to verify properties over networks of automata with a state-space that is too large to traverse is to use statistical model checking (SMC) [15]. Uppaal Stratego supports SMC [9], and has shown promising results in the railway domain over a moving block signalling system [3]. Using SMC, properties are quantified over the probability of occurring, and model-checking involves performing many runs of the system until the confidence reflects the probability of the property. *Uppex* provides an alternative to model-check complex systems, without losing the strength of symbolic model-checking, by facilitating the process of producing many simplifications, each abstracting over different aspects. This family of simpler models is automatically model-checked by successive instantiations and invocations to Uppaal. Although we use the Uppaal model checker, this tool and our methodology can be easily adapted to other model-checkers such as IMITATOR [1] or mCRL2 [6].

The idea of verifying a family of systems efficiently has been investigated and well received in the software product line community [8, 6]. The goal of these approaches is to be able to verify a set of properties in all members of a family of systems. This is often realised by modelling the variability aspect together with the behavioural aspect, avoiding the generation of one model for each member. On the contrary, our approach produces one instance of the model for each member. This creates less dependencies to the choice of the concrete model-checker and allows customising which properties are verified at each instance, at the cost of performance and number of configurations supported. Furthermore, *Uppex* attempts to provide an easy interface between modellers and developers, giving the power to developers to fine-tune parameters and configurations without being exposed to the model-checker.

Uppex uses a Domain Specific Language to represent feature models, for which many textual and modelling languages exist [5]. A feature model is here represented as a spreadsheet table, getting inspiration mainly from the UVL language [19], but exploiting the tabular representation to capture the tree structure of feature diagrams [18].

Several approaches exist to realise variability, i.e., to generate software artefacts from a selection of features [10]. Popular ones include annotative and compositional approaches [2]. Annotative approaches mark code blocks that should be removed when some feature is absent at compile time, e.g. using the C-preprocessor to hide blocks of code using `#ifdef` directives. Compositional approaches, such as feature-oriented programming [4], aspect-oriented programming [14], and delta-oriented programming [17], provide mechanisms to inject blocks of code based on the selected features. *Uppex* uses annotated blocks in a compositional way, i.e., they act as *hooks* marking consecutive lines of the specification file that can be modified when producing variations. This is aligned with the aspect-oriented approach, which uses patterns to discover blocks to be adapted (instead of explicit hooks), and with the delta-oriented approach, which uses the names of structural elements (such as classes, objects, and methods) as the blocks to be adapted. Our approach is more primitive, in the sense that it is not aware of the structure of the documents being adapted. This makes it more independent of the target language and analyser being used in the back-end, at the cost of understanding and reusing the content of the blocks being replaced. For example, *Uppex* cannot keep an existing annotated block and add a new line, but can only replace the full block with a new one.

Organization of the paper. Section 2 provides more details over our motivating railway scenario prior to our extensions. Section 3 describes how to add variability to Uppaal models with *Uppex*, using features and feature models, using a simpler example. Section 4 summarises some lessons learned when using *Uppex*, and Section 5 concludes this paper and suggests lines of future work.

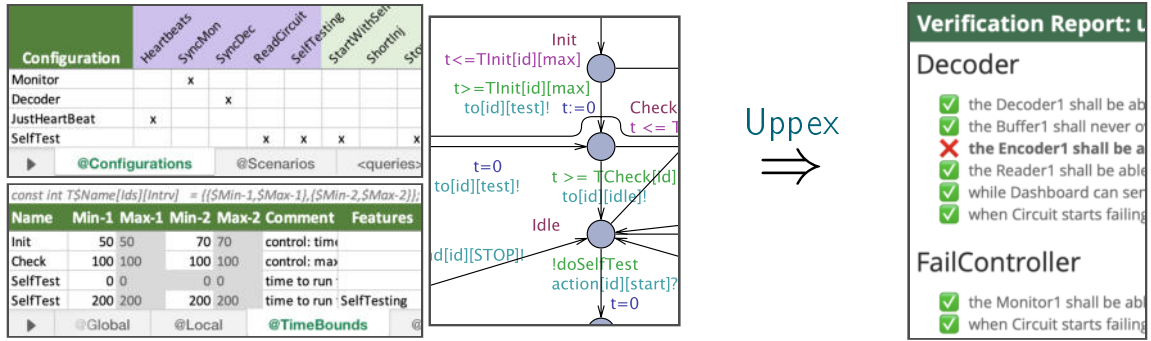


Figure 2: Uppex workflow: updating and verifying models based on configuration tables

- discarded reading from the circuit; and
- discarded part of the controller behaviour (initial tests).

In total, we collected ± 35 aspects that could be toggled, called *features*, and manually selected 14 combinations of these features, called *configurations*. The choice of this combinations was driven by the requirements, i.e., adapted until each requirement could be verified in a rich-enough set of variants. Note that some of these features were describing requirements that must be verified, e.g., if deadlock freedom should be verified. Also note that these features are not meant to be optional features of the implementation, e.g., we always expect the final system to use heartbeats; however, abstracting it away in some variations allows the verification of properties that do not rely on heartbeats.

Statistical Model Checking (SMC), also supported by Uppaal and applied in a similar context [3], is an alternative approach that we avoid. Using SMC one can verify properties with a given level of certainty, based on many runs of the model. However, it does not provide the same level of certainty of traditional symbolic model-checking.

Automatisation with spreadsheets and Uppex

We propose to automatise the verification of these variants, initially reported in RSSRail 2022 [16], using (i) *spreadsheets* to represent both core parameters and requirements of the system under study, and (ii) a prototype tool Uppex¹ to automatise the creation and verification of variations of the formal specification, whereas each variation can have a different set of requirements. Formal models are annotated, specified, and verified using the Uppaal model checker [9]. Uppaal targets real-time systems, using special variables called clocks that capture the passage of time, and using these clocks to guide the behaviour (with some syntactic restrictions that make the model-checking problem feasible).

Uppex is an open-source command-line tool developed in Scala that reads both a set of spreadsheets with configurations in MS Excel and an annotated Real-Time specification in Uppaal. Other back-ends are future work, e.g. IMITATOR [1]. A typical workflow is depicted in Fig. 2: given a set of configuring spreadsheets and an annotated Uppaal specification (left), Uppex produces an html report (right) listing properties that passed, failed, or timed-out for each configuration.

More specifically, Uppex interprets (1) *special sheets from a MS Excel file* and (2) an *annotated Uppaal file* (XML format), briefly described below.

¹<https://cister-labs.github.io/uppeex/>

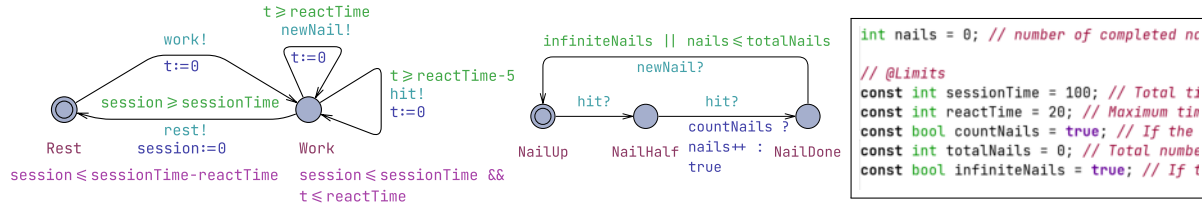


Figure 3: Annotated Uppaal specification of a *worker* (left) and a *hammer* (middle); this specification is an XML file with code snippets (c.f. right side) with c-like code that is used by the automata

- Two types of *annotated blocks* are recognised by *Uppex* in the Uppaal file: (1) a sequence of consecutive lines starting with “`// @BlockName`” until an empty line, such as the “`// @Limit`” block on the right of Fig. 3, and (2) an XML element “`<BlockName>...</BlockName>`”, covering the text between the tags. Both these annotated blocks have an identifier (the *BlockName*) and a consecutive sequence of lines.
- The sheet `@Configurations` (top-left of Fig. 2) lists valid combinations of *features*, describing *configuration names* in the first column and *feature names* in the first row.
- Any other sheet starting with `@`, such as `@Timebounds` (bottom-left of Fig. 2) describe what code will be injected in the Uppaal specification, in this case in an annotated block named `Timebounds`. The column named `Features` is used to filter rows based on the selected configuration – in this case the last two rows have the same identifier (`SelfTest`), and when the `SelfTesting` feature is active the last row will override the previous one. We call these *@-annotations*.
- Any sheet with a name surrounded by `<.>` (e.g. `<queries>`), is similar to an `@`-sheet, but targeting annotated blocks given by XML elements, as explained above. We call these *xml-annotations*.

We will describe each of these tables and annotations in more detail below, guided by a simpler example, and extend this approach to further exploit the analyses of features.

3 Feature modelling in Uppex

In this work we extend *Uppex* to further exploit the feature analysis, introducing *data attributes*, *feature conditions*, and a *feature model*. These are explained below using a simpler but complete example of a *hammer* automaton interacting with a *worker* automata while hitting nails. This example can be found together with the tool at <https://github.com/cister-labs/uppep/blob/v0.1.3/examples>.

3.1 Annotating Uppaal specifications

When developing a family of models with *Uppex*, the starting point is a parameterised model. In Fig. 3 we present a simple example with 2 timed-automata, where a *worker* is either *Resting* or *Working*. While working, it uses a *hammer* to either *hit* a nail or to place a *newNail*. The code on the right side is used by the Uppaal specification; e.g., `sessionTime` represents the combined time to rest and work by the *worker*, set to 100. The other variables, from top to bottom respectively, capture the maximum time to hit a nail or to add a new one, if the nails should be counted, the number of nails, and if no limit of nails should be considered. The details of the semantics of timed-automata are out of the scope of this paper; intuitively each transition can have a *guard* representing when the transition is active, an *action* that will act as a

synchronisation barrier with a counterpart action, and an `update` that updates variables after a transition. Some special variables represent time and are called *clocks*; in our example `t` and `session`.

3.2 Configuring variants

A *configuration* is a variation of the Uppaal specification by replacing an annotated block by a new block with the same name. In our example, the code on the right of Fig. 3 has a `@Limits` block with 5 lines. Using a companion MS Excel spreadsheet, we can specify configurations that describe how these annotated blocks can be replaced.

Configuration	Lazy	Overworker	Slow	Count	Inf
Main					
Lazy	x				
Overwork		x			
SlowLazy	x		x		
NormalCount				4	
SlowCount	x		x	3	

const \$Type \$Name = \$Value; // \$Comment					
Name	Value	Type	Features	Commer	
sessionTime	100	int		Total tim	
sessionTime	50	int	Lazy	Total tim	
sessionTime	200	int	Overworker	Total tim	
countNails	FALSE	bool		If the nai	
countNails	TRUE	bool	Count	If the nai	
totalNails	0	int		Total nur	
totalNails	\$Count	int	Count && !Inf	Total nur	

<query> <formula>\$Formula</formula> <comment>\$C		
Formula	Features	Comment
A[]!deadlock		No deadlocks
A[] W.Rest		The worker is al
E<> H.NailDone		The hammer car
A[] W.Work imply W.t <=20	Lazy	The worker neve
A<> H.NailDone		The hammer mu
W.Work -> W.Rest		The worker mus
A<> nails>=\$Count	Count	The hammer mu

Figure 4: Defining configurations with spreadsheets: selection of features in `@Configuration` (left), defining the `@Limits` annotation (middle), and defining the `<queries>` annotation (right)

The middle of Fig. 4 presents the `@Limits` sheet in our hammer example, containing a table of values that is used to produce the associated `@Limits` annotation block.

This table is called an *@-annotation*. In the new block each line is formatted according to the top row “`const $Type $Name = $Value; // $Comment`”. Blocks can also refer to XML tags, to replace blocks delimited by a given tag; e.g. the sheet on the right of Fig. 4 is an *xml-annotation* that specifies a list of requirements using Uppaal’s logic that will replace the content of the `<queries>` XML element.

A configuration is a set of features, defined in the `@Configuration` table (left of Fig. 4). For example, the configuration named `SlowLazy` includes the features `Lazy` and `Slow`. Features can also have an associated value, e.g., `Count` is assigned to “4” in configuration `NormalCount` and to “3” in `SlowCount`.

The annotation tables (c.f. middle and right of Fig. 4) can have a special column named `Features` with boolean expressions over feature names. This is used to filter rows: given a configuration, only rows with an expression that holds for the corresponding set of feature is considered. Empty expressions are trivially true. Furthermore, the left-most column acts as an identifier: if more than a row with the same identifier is selected, the last one with a valid feature expression is used. We chose to use an *overriding* interpretation, instead of forcing these feature expressions to be disjoint for entries with the same identifier, because we found these specifications to be simpler to write and more compact. In this example selecting the `Overworker` feature and not `Lazy` will discard the 2nd row for `sessionTime`, and the 3rd will override the 1st. I.e., the variable `sessionTime` will be set to 200. The value of a feature can be used in the other cells of a row; e.g., the value of `totalNails` will be set to 4 when choosing the configuration `NormalCount`.

This work extends our previous approach [16] by (i) associating values to features and (ii) using of expressions over features instead of individual features in the `Features` column.

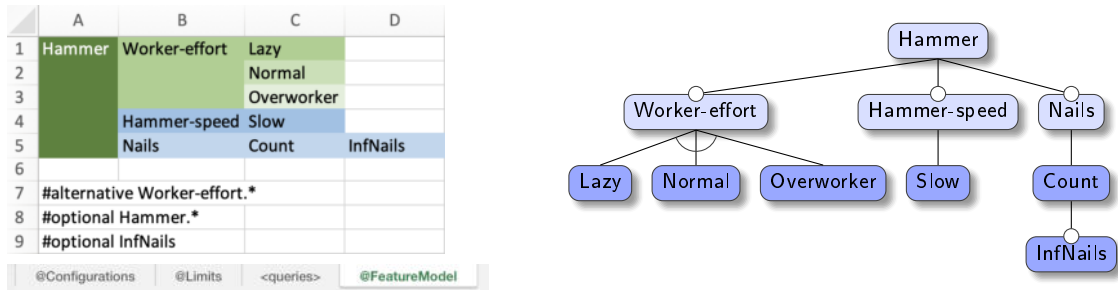


Figure 5: Example of a feature diagram: its tabular form (left) and its usual representation (right)

3.3 Validating features

Not all combination of features in the @Configuration table should be considered. For example, the worker should not be both lazy and overworker. Such constraints are compiled in another special table called @FeatureModel, using a tabular form of feature diagrams [18]. These constraints describe valid combinations of features but are not related to the Feature columns in the annotation tables. We borrowed some constructs from the textual UVL language for feature models [19], and synthesise UVL diagrams in Uppex. An example of a feature diagram can be found in Fig. 5: on the left our tabular representation, and on the right its more traditional visual representation. The table is interpreted as follows.

- Non-empty rows whose 1st column does not start with # describe the **tree structure**: the parents on the left and the children on the right. For example, cell C4 (Slow) is the child of B4 (Hammer-speed), which in turn is the child of A4; the latter cell is empty, meaning that it inherits the previous value in column A, i.e. A1 (Hammer).
- Rows whose 1st column starts with # describe a **constraint**:
 - #mandatory <siblings> – given a set of features with a common parent (siblings), it states that these are mandatory whenever the parent is selected;
 - #optional <siblings> – states that a set of siblings are optional, even if the parent is selected
 - #alternative <siblings> – states that a set of siblings are exclusive and at most one should be included whenever the parent is selected;
 - #or <siblings> – states that at least one out of a set of siblings should be included whenever the parent is selected;
 - #constraint <feature-constraint> – is a boolean formula over features, following the same syntax as in the Features column (c.f. Section 3.2), that must hold.

Only the #alternate and the #optional constraints are illustrated in Fig. 5, and by default all features are mandatory. Combining the tree structure and the constraints yields a feature diagram, such as the one on the right of Fig. 5. Currently Uppex supports feature-constraints over features but not over feature attributes, which is left as future work. The tree structure also imposes a strong need to include parent features whenever a child is selected – Uppex exploits this by automatically expanding the selection of features to all the parents of the selected ones.

3.4 Workflow using Uppex and Uppaal

So far we described how to specify the input models: (i) the annotated Uppaal specification, (ii) the tables with possible parameters and requirements, (iii) the table with configurations of features, and (iv) the table with the feature model. This subsection describes our proposed *methodology*, i.e., the suggested workflow with Uppex and Uppaal during the development of a model.

Uppex's tool is a standalone JAR file `uppex.jar`, open-source and available at <https://github.com/cister-labs/uppex/releases>, that can be executed as a command line tool using `java -jar uppex.jar [options] <mytables.xlsx>`. We expect a typical development of a Uppaal+Uppex project to proceed as follows.

1. **Model:** Produce a base Uppaal model `project.xml`, i.e., a network of timed automata that can be simulated in Uppaal.
Edit: Automata in Uppaal
2. **Parameterise:** Identify a set of parameters that can be useful to expose to domain experts and create the associated `@`-annotations in the companion Excel file `project.xlsx`; update the Uppaal model by running Uppex with no arguments, e.g. `java -jar uppex.jar project.xlsx`.
Edit: Automata in Uppaal & @-annotations in Excel
3. **Verify behaviour:** Identify a set of requirements, specify them using Uppaal's CTL, and place these in the `<queries>` spreadsheet (c.f. right of Fig. 4); update the Uppaal model as before, or verify all properties using Uppex using the command `java -jar uppex.jar --run project.xlsx`.
Edit: <queries>-annotation in Excel
4. **Instantiate:** Identify variability points and features, populating the annotation tables with a Features column (c.f. right of Fig. 4), and create the `@Configurations` table to list products, i.e., desired combinations of features (c.f. left of Fig. 4); transform the working Uppaal file to match any given configuration (or product) `prod` by running `java -jar uppex.jar -p prod project.xlsx`; the verification in step (3) can also receive the `-p prod` option, or simply `--runAll` to verify all available products.
Edit: @Configurations & annotations in Excel
5. **Verify instances:** Identify restrictions over what features can be combined, and specify these in the special `@FeatureModel` table (c.f. Fig. 5); Uppex will always validate all features when verifying or applying a product, but can also be used exclusively for validation by running `java -jar --validate project.xlsx`.
Edit: @FeatureModel in Excel

At each of the steps above it is often needed to revisit the previous steps. E.g., after the verification step (3) we expect to be needed to revisit the model in steps (1) and (2), to adapt it based on the verification results.

When a product is applied, a backup of the original version is stored in a folder `backups`, to prevent losing parameters by mistake. This resembles a naïve implementation of a version-control system, where applying a product modifies the working document, while keeping the history of previous versions.

Verifying properties with Uppaal requires the `verifyta` tool to be available at the command line, called by Uppex using system calls.² After verifying all properties of all products with `java -jar uppex.jar --runAll project.xlsx`, the tool presents a summary of annotations and configurations found, the feature model in plain text using UVL [19], potential errors when validating products, and the

²Uppaal is a commercial tool, but freely available for academic partners.

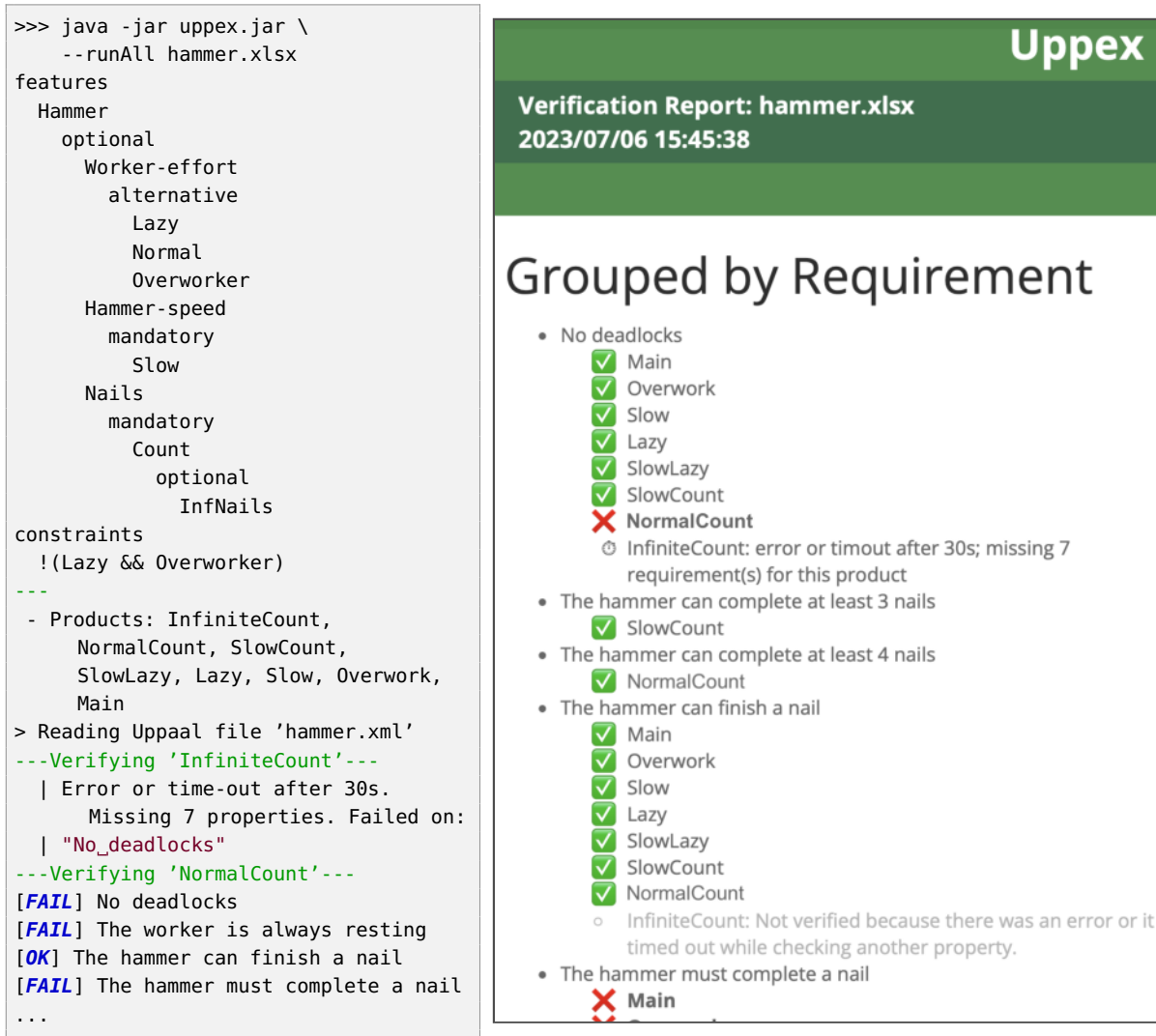


Figure 6: Output when running Uppex to verify all properties in the hammer project: to the prompt (left) and to the report.html file (right)

results from verifying each property. Each property is marked as passed, failed, or threw an error (e.g., time-out). Furthermore, a report.html file is created that clusters these results in a more useful form. The textual output and the HTML report of our hammer example can be found in Fig. 6.

4 Discussion

Our tool and methodology was first applied to our industrial use-case provided by the Alstom railway company on a signalling system, c.f. Section 2. Many of our design decisions were motivated by weekly discussions between academics and practitioners. Some of the insights gained by this collaboration using Uppex are summarised below.

- **Automata size:** The number of automata, locations, and variables easily increased when adding

more details, reaching the 16 automata in Fig. 1. The high level of detail was appreciated by Alstom, as well as the use of variability to enable a precise verification of properties without needing to use statistical model checking approaches.

- **Non-determinism:** The high number of non-determinism resulting from allowing several actions to be taken in any order made it more difficult not only to verify, but also to predict the behaviour of the system. Consequently, a new version of this software is being prepared, with a finer scheduling control that reduces this non-determinism to a minimum.
- **Feature model:** The newly added structure to the features in the feature model contributed to a better understanding and insights of what can be modified in the formal model and how.
- **Attributes:** The possibility of using values in the @Configurations table facilitated the experimentation with different parameters without having to search through different tables for the values to update.
- **Optimal configurations:** The possibility of enriching Uppex to support the search for optimal configurations was considered, but this raised concerns regarding a possible increase of the learning curve to use Uppex. Introducing generic goal functions and cost values could compromise the ease of adoption of Uppex.
- **Feature model size:** As the feature model grows, the number of valid variants grows exponentially with the number of features. In Uppex this was not a concern, since it does neither generate all possible variants nor it attempts to find a variant that obeys some condition. Verifying if a single configuration is valid is computationally simple (linear on the size of the feature model). There is a risk of needing to manually add an increasingly large number of configurations to cover a relevant set of combinations, but we did not encounter this problem in our use-cases.

When compared the Uppex version used in our previous work with Alstom [16], the industrial partners mainly appreciated the possibility of providing numbers in the @Configuration table, avoiding the need to navigate through several other sheets. The added structure to the features brought from the feature model also contributed to a better understanding of what the features precisely captured (and resulted in some restructuring of features). Alstom developers were able to edit a shared Excel spreadsheet to adapt some configuration parameters, and were able to understand the generated html report, although the execution of Uppex with the model-checker was mainly carried by the academic partner. Furthermore, the usage of feature expressions in the Features column instead of single features also simplified our model, avoiding some previously added artificial features used to fine-tune the model.

5 Conclusion and future work

This paper reports on our recent attempt to include feature models represented in our configuring-spreadsheets in an intuitive way for developers, based on feature diagrams with integer attributes, and on how to exploit these for automatic analysis. This work was developed in collaboration with the Alstom railway company, within the VALU3S European project on verification and validation methods and tools.

Our experience showed that, on the one hand, it is useful to adapt the formal model and requirements by using a set of spreadsheets with key parameters. On the other hand it also highlighted that the pivotal notion of features was not yet fully exploited. This work includes support for feature models with attributes while preserving the simplicity of our spreadsheet-based interface, and keeping an easy-to-use solution that can be adopted by practitioners.

Based on the feedback from Alstom, possible ideas for future work include the following.

- **Coverage:** Currently it is possible to quickly grasp which configurations can validate each of the properties. However, it is hard to provide insights over how complete is this coverage, i.e., how much of the full system is validated for any given property. Counting the number of such configurations is a simple but not fully satisfactory approach. A better approach would be to *quantify the scope* of a configuration, e.g., how many locations can be reached, or which out of a set of reference reachability properties can be proven.
- **Other analysers:** We use Uppaal as our underlying model checker, but Uppex is general enough to be applied to other static analysis tools with little effort. For example, by using IMITATOR [1] instead we should be able to verify similar properties with a non-commercial tool and search for optimal parameters, and by using mCRL2 [7] instead we should be able to support the verification of properties focused on actions rather than states.
- **Deployment configurations:** The same configurations' table could be used to guide the customisation of deployment scripts, or other configuration files that can introduce the variability choices in the concrete software implementations.

Furthermore, we invite anyone in the community to submit suggestions or issues using GitHub's issue tracker system, or to contact us for future collaborations.

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