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1 Introduction

This document presents the report for D1.1 ("Classification of existing Validation Obligations and Tools") of the IVOIRE project.

Within the context of software engineering, it is vital to check whether a model meets its specification (verification) and requirements (validation). Various formal techniques exist to verify a requirements model, such as theorem proving or model checking. However, to validate a requirements model, only a few formal techniques are at our disposal. Verification checks that a system or piece of software meets its specification. This means that the program is proven to be correct concerning its specification [100]. **Verification** answers the question: “Are we building the software correctly?” In contrast, **validation** checks whether a model met the stakeholder’s requirements [99]. It answers the question: “Are we building the right software?”.

In general, verification ensures the absence of bugs in the software, e.g., absence of infinite loops, absence of integer overflows. Proof obligations (POs) have been introduced, e.g., for B [1] and Event-B [2] to structure the verification process. A successfully discharged PO ensures the absence of a safety hazard in a model. Validation ensures the presence of certain features. Therefore, a successfully validated system contains desired behaviors, e.g., the ability to perform actions in a specific order.

Verification and validation may overlap, e.g., establishing the presence of a safety property can – depending on the context – be viewed either as verification or validation. Let us consider a safety requirement “The lift can only move when the door is closed.” One may argue that checking this requirement is verification rather than validation. However, the main goal is to check that the stakeholders’ requirements are fulfilled. So, in this context, model checkers and theorem provers, which are primarily verification tools, can also be used for validation.

Compared to verification, validation has received less attention historically in the formal methods community. This is perhaps due to its unprovable nature, as suggested by Rushby: “By their very nature, the problems of validating top-level specifications or statements of assumptions do not lend themselves to definitive proof” [82]. Nonetheless, as outlined by Jacquot and Mashkoor [48], validation within a refinement-based development process is still a challenging task.

In this context, validation obligations (VOs) [70] were introduced to check the compliance of a model with its requirements in a refinement-based software development process. While systematic validation of formal models is not a new concept in the formal methods community, the VO approach is a generic approach independent of a particular formal method or tool.

This report defines the term **validation obligation**, and presents the formalization of VOs and the underlying techniques. More concretely: (1) it formalizes VOs, allowing a combination of tasks and techniques to validate requirements, (2) it proposes semantics that clarifies the dependencies between the associated validation tasks, and (3) it provides a formal basis to trace validation tasks back
VOs must therefore be resilient when more details are added to a model. As requirements are typically expressed in natural language, they can be ambiguous or imprecise. Although a VO aims to be a formal representation, some validation tasks may retain a manual and/or informal component. For example, a certain VO may produce a visualization that still has to be inspected by a domain expert.

First, we will present the classification of requirements (see Section 2). In Section 3, we will discuss the terminologies verification and validation. Then, we define the term validation obligation along with how associated validation tasks are formalized and classified (see Section 4). Here, we also present an overview of existing validation tasks for the modeling languages Alloy, ASM, B, Event-B, VDM, TLA+, Z, CSP, and Circus. Furthermore, we will describe how VOs are used in a refinement-based software development process to validate requirements. Finally, we will demonstrate the VO approach on a Traffic Light model in Section 5.

A glossary containing the basic terms can be found in Appendix A. This report also includes a list of publications in the context of the IVOIRE project Appendix D.

2 Classification of Requirements

By definition according to the IEEE standard 729 [45], a requirement is defined as follows:

1. A condition or capability needed by a user to solve a problem or achieve an objective.
2. A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed document.
3. A documented representation of a condition or capability as in 1 or 2.

This section describes how requirements are classified. In general, they are separated into functional requirements, non-functional requirements, and domain requirements. Furthermore, requirements could also be distinguished between user requirements, and system requirements. [88]

2.1 Functional, Non-Functional, and Domain Requirements

Functional requirements describe how the system should behave. Regarding the general definition of a requirement, functional requirements match the definition of the first aspect. [88]

Thus, functional requirements include descriptions of safety properties, liveness properties, scenarios, probabilistic behaviors, timing behaviors.
In contrast, non-functional requirements describe measurements or constraints for the quality of the software system such as performance, reliability, maintainability, testability, scalability, or security. Thus, non-functional requirements define criteria to evaluate those quality constraints or measurements.

Taking a look at the definition of a requirement, non-functional requirements correspond to the second aspect.

Domain requirements are requirements that have been formulated from a domain expert’s perspective. Therefore, domain requirements can either be functional or non-functional.

Concerning the domain-specific aspect, it might be necessary to refine or abstract the model, projecting on the domain expert’s perspective. Since the model is projected on a specific perspective, state space projection and refinement might play an important role during the validation.

2.2 User Requirements and System Requirements

Requirements could also be distinguished between user and system requirements. User requirements are written from a stakeholder’s perspective, describing the expectation of how a system should behave. Therefore, user requirements usually describe how the user can interact with the model, and check the software’s behavior. In contrast, system requirements describe how software components interact with each other. Thus, system requirements are rather architectural or structural.

3 Verification and Validation

Sometimes the terms verification and validation are used interchangeably. In our report, we use the following definitions. Validation checks whether a model meets the stakeholders’ requirements. So, the main questions are: “Are we building the right software?” and “Are the desired features present?” In contrast, verification checks whether a model meets its specification. So, it tackles the questions: “Are we building the software correctly?”, “Are all safety constraints be enforced?”.

For example, verification ensures that there are no bugs in a model. Properties that correspond to verification (and not validation) are, e.g., the absence of integer overflows or infinite loops. Those properties could be verified by model checking or proving. An example for validation is checking a a requirement described by a scenario. This requirement can be validated by running the software with specific input to observe and check the behavior. While verification and validation are different tasks, they also complement each other. For example, well-definedness checking is classified as verification. However, while finding such an error by model checking, one could store the trace as a test for the corrected model (i.e., desiring the absence of well-definedness errors), which falls within the jurisdiction of validation.
Consider Figure 1 illustrating the role of verification and validation in software development. Verification ensures consistency between specification, design, and implementation. In contrast, validation ensures that the specification, design, and implementation fulfill the stakeholders’ requirements.

One might argue that verification should precede validation as the reverse would waste time and effort: Why should someone try to validate the software’s behavior although the software is incorrect? Nevertheless, this question could also be asked the other way around: Why should someone try to verify the software with the potential to notice that the software does not behave as desired in the end? While there is no definitive answer as it is a subjective question, our position is that since both verification and validation are equally important activities, therefore, should be given equal preeminence.

4 Validation Obligations Approach

This section presents a formalization of validation obligations (VO) and a classification of validation tasks (VT). As explained by Mashkoor et al. [70], refinement plays an important role in the VO approach. Therefore, the formal representation of VO should also provide a basis to transform, refine or abstract VO. Furthermore, this work discusses how VTs are created and how VO are integrated into the software development process.

The idea of a refinement-based software development process assumes that a formal model is developed incrementally, i.e., step-by-step (see Figure 2). This means, that a model’s refinement is created for each development step (black/solid-line arrows). Later down the refinement chain, more requirements are taken into account. VO shall be used to ensure the presence of requirements in a refinement-based software development process.

To achieve this, newly introduced requirements must be validated incrementally at each model’s refinement. Additionally, there might be the need for abstracting (illustrated by the blue/dotted arrows) or specializing/instantiating (illustrated by the red/dotted arrows) the model for a domain expert, only focusing on specific requirements. Note that the concept of refinement is already supported in some formalisms (e.g. B and Event-B), but the concept of multiple distinct abstractions is novel, as far as we are aware.
4.1 Refinement and Refactoring

Refinement is an essential technique to enrich models while ensuring their correctness. As shown in Figure 2, the refinement chain has a crucial role in the context of VOs, too. First, there is the classical refinement chain making up the middle of the figure. Here, the model is consecutively enriched with behavior and details. But there are also instantiation refinements and alternate view refinements going to the left and the right.

**Instantiation Refinements** are those that make a model particular for a use case, e.g., by providing an initialization for the variables.

**Alternate View Refinements** are those that allow a more abstract view onto the model, enabling easier reasoning, e.g., by ignoring behavior that is not relevant to validate a property, showing this property can become easier.

Multiple problems arise from that:

1. How should such refinements interact with each other? On the right-hand side of Figure 2 one can see that $A_2.b$ is refined by $M_2.b$, which is also an instance of $M_2$. It is an ongoing question of how the relationship between these components should be allowed and formally defined in the first place. The problem of these multi-layer relationships is keeping track of the changes and dependencies. Furthermore, every abstraction has to be validated, and in the case of the multi-layer relationship, the abstraction $A_2$ has to be verified as the refinement of the instance of $A_2.b$. Even with the minimal example, this would result in a set of new proof obligations that would have to be shown to ensure a correct refinement in the first place.

Figure 2: Refinement-based Software Development Process with VOs
2. How should VOs be refined? When doing linear refinement, a VO that holds on \( M_1 \) has to hold on \( M_2 \). But what about nonlinear refinement? A VO on \( A_2, b \) has to hold too when going down the refinement chain, but how is this shown? Imagine introducing \( M_3 \) refining \( M_2 \). Does one needs to create an \( A_3, b \) to show the VO? There could be a case where this abstraction is no longer feasible as new behavior entangles components that were only loosely connected before. An idea would be to reduce every VO from a nonlinear refinement back to the origin in the linear refinement chain, which will be researched and discussed in the future.

3. On the right-hand side of Figure 2 one can see a VO transformation. We do not know yet what this means in practice. And what the applications and restrictions are.

   Besides, formal refinement models can be refactored e.g. changing the name of variables, or altering the state space by changing the behavior of operations. In this case, VOs are validated similar to POs. There might be tool support to adapt the VOs and especially their tasks to this in the future. For now, this is not an immediate concern as refactoring should not change the behavior of a model but the quality of life of the modeler.

4.2 Definition of Validation Tasks

Before we define the term VO, we will first formalize the subsidiary concept of a validation task (VT). A validation task (VT) is identified with an identifier, and consists of a validation technique that is applied with the given validation parameters to the corresponding context. Executing a VT possibly modifies the internal state of the validation tool, e.g., consisting of the currently explored state space, and the current trace. The notation we will use for a VT is as follows:

\[
\text{VT}_{id}/\text{VT}_{context}/\text{VT}_{technique}: \text{VT}_{parameters}
\]

4.3 Classification of Validation Techniques

In the following, we explain various validation techniques, and how they are formalized as validation tasks. There are various validation techniques one can use to validate a requirement. Table 1 contains an overview of VTs we have assembled while conducting or inspecting a variety of case studies. These case studies range from academic case studies (e.g., the ABZ landing gear case study \([57]\), and the ABZ automotive case study \([63]\) to industrial applications in the railway industry (e.g., \([41, 24]\)). Regarding the future, Table 1 and operators might gradually evolve for new case studies or applications. When explaining each validation technique, we refer to the name column in Table 1. Overall, VTs in Table 1 are expressed at a high level to keep the table generic. The VO approach intends to work independently of the used formalism and tool.
Valiation by Animation, Trace Replay, Testing Animation makes it possible for a human to execute the model interactively. Some animators explore all transitions from the current state to the succeeding states. This is done by interpreting the operational semantics of the used formalism on the model with all possible values for parameters and variables that are assigned non-deterministically. Regarding the notion for a transition, possible means that the corresponding guard is met [48, 68, 71].

The main advantage of animation is that the user can interact with the model and view the model’s state after executing an action. Thus, this validation technique makes it possible to reason about the model more easily. When an animator explores all succeeding transitions, the user also gets the information on which actions can be applied outgoing from the current state. This eases the interaction with the model in a way that the user does not need to think about which input parameters are required to constraint the guard. Nonetheless, it is then necessary to iterate over the possible values for parameters and non-deterministically assigned variables which leads to a combinatorial explosion of possible transitions. [48]

Outgoing from an animation process, the modeler could store the resulting trace representing a scenario with certain behaviors. Later on, the trace can be used to re-play the scenario, i.e., to check whether the scenario is still re-playable from the model (realized by TR). Trace replay is applied similar to animation, but with the main difference that it is done automatically.

A trace $T$ consists of a list of the transitions $t_1, \ldots, t_n$. For each transition, the modeler could optionally add a predicate $\psi$ to be checked after re-playing the transition. Here, we will use the notation $t <\psi>$ for a transition $t$ and a predicate $\psi$. If there is no postcondition, we will use the notation $t$ only.

Traces can then also be viewed as acceptance and unit tests which are well-known in traditional programming practice. Thus, they can then be used to ensure the presence of certain behaviors in the model.

Note that the form of a transition depends on the used formalism. E.g., in the B method, a transition consists of the operation’s name, the values for parameters, and the values for non-deterministic assigned variables.

Validation by Simulation Simulation such as co-simulation [97] or timed probabilistic simulation [101] can be used to execute a model automatically. Here, the modeler can define respective configurations or annotations to define simulation scenarios. Monte Carlo simulation [74] can be applied in the context of timed probabilistic simulation to generate a various number of simulations. Based on the resulting execution runs, statistical validation techniques such as hypothesis testing [51] (realized by HT), or estimation of probability [31] (realized by EOP) can be applied to show the presence of a behavior [101].

Sometimes, systems consist of several different components or subsystems that interact with each other. Each subsystem might be embedded into a different tool, or even modeled with a different formalism. Co-simulation implements the idea of combining the components into an overall system for simulation.
In particular, the subsystems and their communication with each other are simulated in parallel. Regarding the communication itself, subsystems must exchange data with each other which again might trigger events.

Regarding timed probabilistic simulation, the modeler can simulate the underlying model with timing and probabilistic behavior. Each simulation results in a trace where each executed event is annotated with a certain time, called timed trace. A timed trace can then be replayed in real-time, i.e., wall-clock time.

**Validation by Test Case Generation**  Test case generation tries to satisfy a given coverage criterion by generating tests for a model. The desired coverage criterion is satisfied if each possible branch is covered by a test. Thus, each generated test is represented by a trace which can be seen as a scenario representing a certain property. Therefore, test case generation is a validation technique that can be used to generate new scenarios which again can be validated by animation, trace replay, and testing. Coverage criteria include operation coverage (realized by OC) and MC/DC coverage (realized by MCDC). While the goal of operation coverage is to cover each operation, MC/DC coverage is used to cover all possible outcomes of each operation [13, 84, 104].

**Validation by Model Checking**  Explicit-state model checking checks state-based behaviors of a system by exploring its state space exhaustively (realized by MC). Exhaustive exploration leads to full coverage of the system’s behavior when the model checking process terminates. Furthermore, it is then ensured whether the property is fulfilled or not. In the case that a property is violated, explicit-state model checking can return a counter-example. Again, when applying model checking to find a state satisfying a certain property, the technique can also provide a path leading to this state. Nevertheless, explicit-state model checking often struggles with the combinatorial explosion of the state space which is called the state space explosion problem. This is because the number of states in a state space grows exponentially wrt. the number of variables in a model. [7]

Temporal model checking includes LTL and CTL model checking. LTL model checking checks a temporal property (expressed as LTL formula) that is expected for the given system (realized by LTL). Using the transition system and the Büchi automaton that is created from the LTL formula, LTL model checking checks temporal properties which are more complex than state-based properties. When negating the LTL formula, one is also able to find an example where the temporal property is true. [7]

To formulate more expressive temporal properties, the modeler could also write CTL formulas and apply CTL model checking (realized by CTL). Compared to LTL, CTL supports the operators $A\phi$ ($\phi$ is true for all paths), and $E\phi$ (it exists at least one path where $\phi$ is true). [7]

As the state space is also explored exhaustively, there are the same advantages and disadvantages as explicit-state model checking. [7]
Symbolic model checking (realized by SMC) bases on the idea of getting rid of the state-space explosion problem. To achieve this, the state space is not explored explicitly. Instead, logical formulae are derived from the model and then checked for solutions where properties are violated. Symbolic model checking makes use of techniques such as SMT solving and abstract interpretation which are realized in the algorithms for constraint-based model checking, bounded model checking, k-Induction and IC3 etc. As the symbolic evaluation of the model is an over-approximation, there might be some false positives. Furthermore, the counter-example might also be abstracted which leads to a loss of information. [54]

By assigning probabilities to events in a model, a state space could be generated on which transitions are labeled with probabilities. As result, the state space can be viewed as a Markov chain on which probabilistic model checking can be applied to validate probabilistic properties. It is also possible to validate probabilistic temporal properties, e.g., properties that are encoded with PLTL, PCTL, or PB-LTL formulas. Similar to probabilistic model checking, statistical model checking also aims to check probabilistic properties. The main difference is that statistical model checking applies Monte Carlo simulation, whereupon PB-LTL or BLTL formulas are checked with hypothesis testing or estimation. [59] [60] Both model checking techniques are realized by PSMC.

As mentioned before, timed probabilistic simulation also applies Monte Carlo simulation together with statistical validation techniques. However, timed probabilistic simulation does not check temporal formulas. Instead, the modeler can specify a property (with timing behavior if desired) along with a start and end condition which should be checked. [101]

**Validation by Proving** Proving is a technique that is used to ensure the model’s consistency, i.e., to show the correctness of the program in certain aspects. To achieve this, proving is often applied to proof obligations which are formulas that are generated from the model (realized by PO). Relevant aspects could be e.g., the violation of invariants, deadlocks, well-definedness errors, or refinement errors. The process of proving itself is both automatic and interactive [2].

In practice, different solvers are applied to try to prove a formula. However, solvers are sometimes not strong enough to prove a formula. The proof must then be done by the user interactively with additional effort.

The main purpose of proving is to ensure that the model does not contain any errors which seems to be rather verification than validation. As discussed in Section [3] we also see proving as validation.

**Validation by Visualization, Statistics, and Metrics** Another category of validation techniques includes inspection of visualizations, tables, statistics, and metrics. The following VTs we consider are:

- **State Space Visualization:** One of such techniques includes visualizing and inspecting the whole state space after applying certain steps. For a given
state space consisting of reachable states, and possible transitions, one can formulate a predicate over the state space to be checked. This is realized in \textit{SVIS}.

- \textit{State Space Projection}: In practice, state spaces often become very large due to the state space explosion problem. As result, the visualization gets too complex to understand. To solve this problem, the modeler could provide an expression to create a state space projection onto this expression. This results in an abstract visualization of the state space which is easier to understand. \cite{56} Similar to the state space inspection, one could also formulate a predicate to be checked over a projected state space (realized by \textit{SPRJ}). The projected state space could also provide a base to apply other VTs, e.g., LTL model checking.

- \textit{Enabling Diagram}: An enabling diagram is a diagram that describes for each operation which operations is enabled after executing this operation \cite{29}. This helps to inspect how operations could depend on each other. The corresponding VT (see \textit{ED}) expects a formula that is checked over the diagram.

- \textit{Operation Coverage Table}: This table describes for each operation whether it is covered yet. Formally, one can provide a formula that is checked on the table as shown in \textit{OCT}. Combining this task with other VTs, one can evaluate the coverage of the other VTs. For example, \textit{OCT} could be applied after running a set of scenarios. Afterwards, one can then measure the coverage, and thus also the quality of the given set of scenarios.

- \textit{Read/Write Matrix}: The read/write matrix is a table describing for each operation which variables are read and written. Similarly, one can inspect this matrix by checking a certain predicate (realized in \textit{RWM}). This helps to inspect which parts of a state are influenced by an operation and vice versa.

- \textit{Variable Coverage Table}: This table provides the number of values a variable has been assigned to. Similarly, one can also provide a predicate that is checked over the table (realized in \textit{VCT}). This task is usually also combined with other VTs, to evaluate their coverage wrt. to the model’s variables.

- \textit{Min/Max Values for Variables}: This table shows the minimum and maximum value each variable has been assigned to. Based on the table, one can also formulate a predicate which is checked on the table as shown in \textit{MMV}. In combination with other VTs, this task also helps to inspect the coverage. For example, one can then inspect why the state space explodes.

- \textit{State Space Statistics}: To validate a model, the modeler could also take state space statistics into account. Interesting statistics for the state space, could be, e.g., the number of states, or the number of transitions. One
could also extract more complex statistics, e.g., the number of states with a certain property such as invariant violation, deadlock, or liveness. To determine which events are particularly important for the model, one could also take the number of transitions for each event into account. This task is also formalized with a predicate over the state space statistics as shown in STAT.

- Simulation Statistics: Based on a model and a simulation, one can also inspect simulation statistics. Interesting properties are, e.g., statistics about how frequently an operation is executed in the simulation. One could also inspect the percentage of how frequently an operation is executed when it is enabled. Similar to STAT, this is also formalized with a predicate over the statistics (see SISTAT).

Vacuous Guards/Invariants: There are also requirements made about the model’s internal structure, rather than its functionality. For example, there could be a requirement, desiring that there are no vacuous parts in the invariant or an operation’s guard. Therefore, we have introduced the corresponding VT which is formalized as VAP.

Example: For example, the following VT identified by LTL$_1$ means that LTL model checking should be applied with the LTL formula $G\{tl\text{peds} = \text{red} \lor tl\text{cars} = \text{red}\}$ expecting a successful result in the Traffic Light model.

| LTL$_1$/TrafficLight/LTL: $G\{tl\text{peds} = \text{red} \lor tl\text{cars} = \text{red}\}$, SUCCESS |
|---|

Code Generation for Validation In contrast to the aforementioned techniques, we do not see code generation as a validation technique directly. Instead, it is rather a tool that can be applied to enable other validation techniques afterwards.

During the software development process using formal methods, software is specified and refined step by step. Once a refinement level is reached which is close to implementation constructs, a code generator is applied. Regarding the B method, a code generator for embedded systems can be applied once the B0 language is reached, which is the implementable subset of B [23]. As an implementable subset of the specification language is required, memory usage of the final refinement can be verified. Thus, the generated code can be used for embedded systems. Additionally, the software engineer could also write or generate tests to validate the generated code. This also means that these validations are applied at the very end of the software development process.

Communication with the stakeholder and early-stage validation is particularly important in the context of VOs. To achieve this goal, our approach intends to take high-level code generators such as B2Program [102] into account. B2Program is suitable for application for early-stage validation of the
Table 1: Classification of Validation Tasks

| Name        | Task                          | Context                  | Parameters | Discharged |
|-------------|-------------------------------|--------------------------|------------|------------|
| TR 3 5      | Trace Replay/Animation        | Model                    | Trace T    | Automatic  |
| HT 4 6      | Simulation + Hypothesis Testing | Model, Simulation         | Hypothesis H 3, Significance level α | Automatic |
| EOP 4 6     | Simulation + Estimation of Probability | Model, Simulation         | Property P 3, Delta value δ | Automatic |
| OC 4 6      | Operation Coverage Test Case Generation | Model | Operations O | Automatic |
| MCDC 4 6    | MC/DC Test Case Generation    | Model                    | Level l    | Automatic  |
| MC 4 5 6    | Explicit-state Model Checking | Model                    | Configuration c ∈ ConfigMC, p | Automatic |
| SMC 6       | Symbolic Model Checking       | Model                    | Configuration c ∈ ConfigMC, p | Automatic |
| LTL 4 5 6   | LTL Model Checking            | Model                    | LTL Formula ψ, c ∈ {SUCCESS, FAIL} | Automatic |
| CTL 4 5 6   | CTL Model Checking            | Model                    | CTL Formula ψ, c ∈ {SUCCESS, FAIL} | Automatic |
| PSMC 4 6    | Probabilistic/Statistical Model Checking | Model | Probabilistic Temporal Formula ψ 3, | Automatic |
| TR           | Trace Replay/Animation        | Model                    | Trace T    | Automatic  |
| ED 7        | Inspection of Enabling Diagram | Model                    | Formula ψ over enabling diagram | Manual |
| OCT 8       | Inspection of Operation Coverage Table | Model | Formula ψ over operation coverage table | Manual |
| RWM 8       | Inspection of Read/Write Matrix | Model | Formula ψ over read/write matrix | Manual |
| VCT 8       | Inspection of Variable Coverage Table | Model | Formula ψ over variable coverage table | Manual |
| MMIV 8      | Inspection of Min/Max Values | Model                    | Formula ψ over min/max values table | Manual |
| VAP          | Vacuous Parts Check Model     | Model                    | Configuration c ∈ [GRD, INV] | Automatic  |

1. succeeds when scenario is replayable and all tests succeed
2. succeeds when ψ is fulfilled for SUCCESS or ψ failed for FAIL
3. depends on the tool that is used
4. explores state space
5. updates current trace (model checking only for FAIL and GOAL)
6. generates (counter)-examples for a domain expert
7. generates visualization for a domain expert
8. succeeds when formula is fulfilled on visualization, table, statistics, ...
9. P_{stat} and P_{result} denote the respective set of (simulation) statistics properties
10. E denotes the set of events/operations, V denotes the set of variables
11. τ(ψ) denotes the set of all values which can be of ψ’s type

Remark: ConfigMC, p is currently defined as \(<\text{FIN}, <\text{DLF}>\> \cup \{<\text{INV}, \psi > | \psi \in F\} \cup <\text{GOAL}, \psi > | \psi \in F\rangle\), where F denotes the set of formulas in the supported formalism, FIN denotes checking for finite state-space, DLF denotes checking for deadlock-freedom, INV denotes invariant checking, and GOAL denotes searching for a goal.
software, but cannot be used to generate code for embedded systems. Based on the generated code, the model could then be animated, tested, and simulated. As the model is translated to a programming language, it could also be more familiar to the domain expert to work with it compared to working in the context of formal methods.

**Languages and their tools** For our research we have investigated nine major modeling languages regarding their tool support for different tasks. The results are shown in Table 2. Whenever something is marked with $\times$, we did not find referable evidence for the existence of the respective tool support. A more comprehensive evaluation of state-based formal methods is provided by Mashkoor et al. [69].

One can see that tool support is widely spread. As we use the ProB platform as starting point for further development, the B and Event-B languages are especially appealing as they are covered by most of the features we investigated.

| Tools | Alloy | ASM | B | Event-B | VDM | TLA+ | Z | CSP | Circus |
|-------|-------|-----|---|---------|-----|------|--|-----|--------|
| Animation | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Trace Replay/Testing | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Test Case Generation | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Simulation | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Explicit-State MC | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| LTL MC | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| CTL MC | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Symbolic/Statistical MC | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Proving | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Refinement Checking | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| State Space Visualization | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |
| Code Generation | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] | ![X] |

### 4.4 Definition of Validation Obligation

We define the term *validation obligation* (VO) as follows:

A *validation obligation* (VO) is composed of (multiple) validation tasks (VT) associated with a model to check its compliance with the requirement.

Thus, validating a requirement succeeds if all associated VOEs yield successful results. Formally, a VO is annotated with an id, and consists of a *validation expression* (VE). The VE consists of operations on the associated VTs. Therefore, a VO succeeds, if the corresponding VO expression leads to a successful result. The notation we will use for a VO is as follows:

---

1In Alloy, it seems that it is not possible to animate the model interactively. Nonetheless, it is still possible to test the feasibility and behavior of a scenario. Here, it seems that scenarios have to be encoded manually. Furthermore, note that Alloy only supports infinite traces

2High-Level Code Generation for (Early-Stage) Validation

---
**VO\_id : VO\_{expression}**

An example for a VO that validates \texttt{LTL\_1} is shown in \texttt{VO\_1}. \texttt{VO\_1} succeeds if \texttt{LTL\_1} discharges successfully.

\[
\texttt{VO\_1} : \text{validate}(\texttt{LTL\_1})
\]

A VE with a single VT \(T\) succeeds if \(T\) succeeds. For a VE \(T\), we allow the unary operator \(
\neg T
\) which succeeds if validating \(T\) fails. For two VEs \(T\_1\) and \(T\_2\), we allow the following logical operators: \(T\_1 \land T\_2\) (\(T\_1\) and \(T\_2\) must succeed), \(T\_1 \lor T\_2\) (\(T\_1\) or \(T\_2\) must succeed), \(T\_1 \Rightarrow T\_2\) (if \(T\_1\) succeeds then \(T\_2\) must succeed as well), \(T\_1 \Leftrightarrow T\_2\) (\(T\_1\) must succeed when \(T\_2\) succeeds and vice versa). Additionally, we also consider the sequential composition \(T\_1; T\_2\) which means that \(T\_2\) is executed after \(T\_1\), based on \(T\_1\)'s result. Thus, \(T\_1; T\_2\) succeeds, if \(T\_1\) succeeds, and \(T\_2\) succeeds after executing \(T\_1\). For example, \(T\_1\) could apply model checking searching for a state, which is then used as the initial state of a trace replay task \(T\_2\). Regarding the future, the set of operators might evolve.

We also implemented a semantic checker to check the VE’s consistency. For example, evaluating the coverage without applying any tasks before does not have a meaning and therefore is semantically wrong.

### 4.5 Creating Validation Obligations

Currently, a VO is created by the modeler manually. There are also tools like UML-B \cite{86}, which attempt an automatic translation from the specification to a model. Regarding the future, one could explore whether and how VOs can be extracted from the requirements automatically. Here, we could take FRETIish or SPEAR into account to write behavioral requirements in natural language.

When creating a VO, the modeler needs significant knowledge about the modeling language, and about the environment and the techniques to create suitable tasks. For example, the preservation of an invariant can be shown by model checking or proving. Proving and symbolic model checking are therefore more suitable than explicit-state model checking to check an invariant in an infinite-state system. Another aspect is to check whether the property formulated in the VO actually captures the stakeholders’ needs. As natural language is ambiguous, communication and feedback from the stakeholders are important.

### 4.6 VO-guided Workflow

Requirements engineering and software development are highly entangled processes. During the software development process, requirements are encoded into the model incrementally. When validating those requirements, stakeholders and developers get a better understanding of the system which might lead to new requirements being discovered, or existing requirements evolving or being changed. In the case that a VO fails, the modeler needs to re-consider the VO, the requirement, or even the model. Possible questions that could be asked are:
• Did we translate the requirement into a VO, a VT task or the model poorly?
• Does the requirement collide with other requirements? As a result, we may need to weaken or strengthen this or other requirements.

Another important aspect is requirements engineering, to structure requirements systematically, and to define dependencies between them. For example, there are languages such as KAOS [58], DOORS [44], or Problem Frames [47]. Furthermore, there is also PRoR which defines an approach to structure requirements [49]. Concerning refinement and traceability, it will also be important to define dependencies between requirements and thus also VOs. Therefore, we will also take those aforementioned works into account.

5 Demonstration of Validation Obligations

In this section, we will demonstrate how VOs can be used to validate requirements.

Requirements Let us consider a small traffic light example, modeling the cars’ traffic light and the pedestrians’ traffic light at a crossing in Germany, with the following requirements:

FUN1: There are two traffic lights: the cars’ traffic light and the pedestrians’ traffic light. Initially, both traffic lights are red.

FUN2: Cars’ traffic light can switch to red and yellow, if it is red and the pedestrians’ traffic light is red.

FUN3: Cars’ traffic light can switch to green, if it is red and yellow and the pedestrians’ traffic light is red.

FUN4: Cars’ traffic light can switch to yellow, if it is green and the pedestrians’ traffic light is red.

FUN5: Cars’ traffic light can switch to red, if it is yellow and the pedestrians’ traffic light is red.

FUN6: Pedestrians’ traffic light can switch to green, if it is red and the cars’ traffic light is red.
**FUN7**: Pedestrians’ traffic light can switch to red, if it is green and the cars’ traffic light is red.

**SAF1**: One of both traffic lights is red at any moment.

**SAF2**: Cars’ traffic light can either be red, red and yellow, yellow, or green.

**SAF3**: Pedestrians’ traffic light can either be red, or green.

**LIV1**: The situation that both traffic lights are red occurs infinitely often.

**SCENARIO1: Running Cycle for Cars’ Traffic Light:**
In the beginning, the cars’ and the pedestrians’ traffic light are both red. The cars’ traffic light then switches from red to red and yellow. Afterwards, it switches from red and yellow to green. Now, it switches back to yellow, and then to red. The pedestrians’ traffic light stays red during the scenario.

**SCENARIO2: Running Cycle for Pedestrians’ Traffic Light:**
In the beginning, the cars’ and the pedestrians’ traffic light are both red. The pedestrians’ traffic light switches from red to green. Afterwards, it switches back from green to red. The cars’ traffic light stays red during the scenario.

Furthermore, this report also considers additional functional requirements **FUN8**, **FUN9**, and **FUN10** in a refinement. These requirements will not be validated in this report.

**FUN8**: A controller can send a command to switch a traffic light to a specific color, if there are no other commands queued.

**FUN9**: A traffic light can only switch its color if there is a corresponding command queued.
Encoding those functional requirements leads to the B model described in Listing 1.

```
MACHINE TrafficLight
SETS colors = {red, redyellow, yellow, green}
VARIABLES tl_cars, tl_peds
INVARIANT tl_cars : colors & tl_peds : (red, green) & 
( tl_peds = red or tl_cars = red ) 
INITIALISATION tl_cars := red || tl_peds := red
OPERATIONS
  cars_ry = SELECT tl_cars = red & tl_peds = red THEN tl_cars := redyellow END ;
  cars_y = SELECT tl_cars = green THEN tl_cars := yellow END ;
  cars_g = SELECT tl_cars = redyellow THEN tl_cars := green END ;
  cars_r = SELECT tl_cars = yellow THEN tl_cars := red END ;
  peds_r = SELECT tl_peds = green THEN tl_peds := red END ;
  peds_g = SELECT tl_peds = red & tl_cars = red THEN tl_peds := green END
END
```

Listing 1: Traffic Light Example

To demonstrate state space projection, Listing 1 will be refined. Regarding Classical B, it is not only necessary to add new events in the refinement, but also to add them in the abstract machine refining skip. The resulting machines are shown in Listing 4 and Listing 5.

After encoding commands to switch the traffic lights’ colors (FUN8 - FUN10), a domain expert might be interested in sending commands without considering the traffic light’s color only. Here, the domain expert could define a diagram describing how the logic for sending commands has to work. This is shown in PRC1 in Figure 3.

Based on the model, the designer could also run different simulations. Listing 2 shows a SimB file that annotates operations with times and probabilities. Within the first simulation shown in Listing 2, the controller

```
{"activations": [ 
{"id":"$ initialise_machine", "execute":"$ initialise_machine", 
"activating":"choose"},
{"id":"choose", "chooseActivation":{"cars_ry": "0.5", "peds_g": "0.5"}},
{"id":"cars_ry", "execute":"cars_ry", "after":5000, "activating":"cars_g"},
{"id":"cars_g", "execute":"cars_g", "after":500, "activating":"cars_y"},
{"id":"cars_y", "execute":"cars_y", "after":5000, "activating":"cars_r"},
{"id":"cars_r", "execute":"cars_r", "after":500, "activating":"choose"},
{"id":"peds_g", "execute":"peds_g", "after":5000, "activating":"peds_r"},
{"id":"peds_r", "execute":"peds_r", "after":5000, "activating":"choose"} 
] }
```

Listing 2: Traffic Light Simulation (TrafficLight_Sim)

FUN10: A command can be rejected after it has been sent by the controller.
chooses between the cars' traffic light's cycle and the pedestrians' traffic light's cycle with a probability of 50% for each. Whenever a traffic light turns green or red, it will not switch the color for 5 seconds. Switching the cars’ traffic light from red and yellow to green, and yellow to red always takes 500 ms.

Based on this simulation, the modeler could then validate the probabilistic timing requirements PROB-TIM1 and PROB-TIM2.

**PROB-TIM1:** Whenever both traffic lights are red, the cars’ traffic light will turn green with a probability of at least 80% within the next 30 seconds.

**PROB-TIM2:** Whenever both traffic lights are red, the pedestrians’ traffic light will turn green with a probability of at least 90% within the next 30 seconds.

Based on the encoded model, the non-functional requirements are as follows: After validating **SCENARIO1** and **SCENARIO2**, the following coverage criteria are expected to hold: **COV1**, **COV2**, and **COV3**.
**COV1:** Validating SCENARIO1 and SCENARIO2 covers the model such that the cars’ traffic light switches between four colors, while the pedestrians’ traffic light switches between two colors.

**COV2:** Validating SCENARIO1 and SCENARIO2 covers all operations in the model.

**COV3:** Validating SCENARIO1 and SCENARIO2 covers the whole state space consisting of six possible states (including root) and seven possible transitions.

**STRUC1:** tl_cars is written by cars_r, cars_y, cars_g, cars_g only.

**STRUC2:** tl_peds is written by peds_r and peds_g only.

**STRUC3:** There are no vacuous parts in the invariant and guards of the model.

**STRUC4:** The operations enable each other as follows: cars_r enables cars_g, cars_g enables cars_y, cars_y enables cars_r, cars_r enables cars_r and peds_g, peds_g enables peds_r, peds_r enables peds_g and cars_r.

**STRUC5:** All operations are coverable in the model.

**STRUC6:** MC/DC coverage with level 2 should be feasible in the model.

**Validation by VOs** Now, we will describe how all these requirements are validated by VOs. Particularly, we will present at least one VO for each requirement. Since the requirements described above do not necessarily have to be validated by VTs from all types, we will also present alternative VTs to demonstrate all VT types. Here, we will mainly focus on validation in ProB. Furthermore, the VOs are formalized using operators in the B method. Regarding probabilistic model checking, we will also take an example in PRISM into account. In order to validate **FUN1**, it is necessary to check whether both traffic lights are red in all initial states. Thus, this requirement could be validated
by a VO applying an LTL model check to expect a positive result, as shown in VO1.

\[
\text{LTL1/TrafficLight/LTL: } \{\text{tl\_cars = red} \land \text{tl\_peds = red}\}, \text{ SUCCESS}
\]

\[
\text{VO1: LTL1}
\]

For validation of FUN2, one needs to check that whenever the cars’ traffic light is red and yellow, it has been red and yellow since both traffic lights are red, one step ago. Thus, this behavior can be validated by a VO applying an LTL model check to expect a positive result as shown in VO2.

\[
\text{LTL2/TrafficLight/LTL: } \text{G } (\{\text{tl\_cars=redyellow}\} = \Rightarrow (\{\text{tl\_cars=redyellow}\} S \{\text{tl\_cars=red} \land \text{tl\_peds=red}\})), \text{ SUCCESS}
\]

\[
\text{VO2: LTL2}
\]

For validation of FUN3, one needs to check that whenever the cars’ traffic light is green, it has been green since the cars’ traffic light is red and yellow, and the pedestrians’ traffic light is red, one step ago. Thus, this behavior can be validated by VO3 which applies an LTL model check LTL3 to expect a positive result.

\[
\text{LTL3/TrafficLight/LTL: } \text{G } (\{\text{tl\_cars=green}\} = \Rightarrow (\{\text{tl\_cars = green}\} S \{\text{tl\_cars=redyellow} \land \text{tl\_peds=red}\})), \text{ SUCCESS}
\]

\[
\text{VO3: LTL3}
\]

For validation of FUN4, one needs to check that whenever the cars’ traffic light is yellow, it has been yellow since the cars’ traffic light is green, and the pedestrians’ traffic light is red, one step ago. This behavior is also validated by a VO applying an LTL model check expecting a positive result.

\[
\text{LTL4/TrafficLight/LTL: } \text{G } (\{\text{tl\_cars=yellow}\} = \Rightarrow (\{\text{tl\_cars=yellow}\} S \{\text{tl\_cars=green} \land \text{tl\_peds=red}\})), \text{ SUCCESS}
\]

\[
\text{VO4: LTL4}
\]

For validation of FUN5, one needs to check two behaviors:
• The cars’ traffic light might change its color unequal red (realized by LTL5.1).

• Assuming that the cars’ traffic light has already switched its color unequal to red: Whenever the cars’ traffic light is red, it has been red since the cars’ traffic light is yellow, and the pedestrians’ traffic light is red, one step ago (realized by LTL5.2).

While the first property is expected to fail, the second property is expected to hold. Regarding the first behavior, it would also be possible to apply explicit-state model checking searching for a goal. The validation is realized in VO5.

\[
\text{LTL5.1}/\text{TrafficLight/LTL}: \neg (F\{tl\_cars \neq \text{red}\}), \text{FAIL}
\]

\[
\text{LTL5.2}/\text{TrafficLight/LTL}: (\{tl\_cars = \text{red}\} W (\{tl\_cars \neq \text{red}\} \land G(\{tl\_cars=\text{red}\} \Rightarrow (\{tl\_cars=\text{red}\} S (\{tl\_cars=\text{yellow} \land tl\_peds=\text{red}\})))), \text{SUCCESS}
\]

VO5: LTL5.1 \land LTL5.2

For validation of FUN6, one needs to check that whenever the pedestrians’ traffic light is green, it has been green since the cars’ traffic light is red, and the pedestrians’ traffic light is red, one step ago. This behavior is validated by VO6 applying an LTL model check LTL6 expecting a positive result.

\[
\text{LTL6}/\text{TrafficLight/LTL}: G (\{tl\_peds=\text{green}\} \Rightarrow (\{tl\_peds=\text{green}\} S (\{tl\_cars=\text{red} \land tl\_peds=\text{red}\}))), \text{SUCCESS}
\]

VO6: LTL6

For validation of FUN7, one needs to check two behaviors:

• The pedestrians’ traffic light might change its color unequal red.

• Assuming that the pedestrians’ traffic light has already switched its color unequal to red: Whenever the pedestrians’ traffic light is red, it has been red since the cars’ traffic light is red, and the pedestrians’ traffic light is green, one step ago.

Both behaviors can be formulated as an LTL model check, too. While the first property is expected to fail, the second property is expected to hold. Regarding the first behavior, it would also be possible to apply explicit-state model checking searching for a goal. The validation is realized in illustrated in VO7.
The properties for SAF1 - SAF3 can be encoded as invariants. Thus, they can be validated by an explicit-state model check, an LTL model check, or a symbolic model check. In the following, we will validate them by VOs (VO8 - VO10) applying respective explicit-state model checks (MC1 - MC3).

Validation of SAF1:

MC1/TrafficLight/MC: <INV, tl_cars = red or tl_peds = red>

VO8: MC1

Validation of SAF2:

MC2/TrafficLight/MC: <INV, tl_cars ∈ {red, redyellow, yellow, green}>

VO9: MC2

Validation of SAF3:

MC3/TrafficLight/MC: <INV, tl_peds ∈ {red, green}>

VO10: MC3

In contrast, LIV1 is a requirement describing a liveness property. Thus, it can be checked by VO11 validating an LTL model check to expect a positive result as formalized in LTL8.
LTL8/TrafficLight/LTL: \( GF(\{tl_{cars} = \text{red} \land tl_{peds} = \text{red}\}) \), SUCCESS

VO11: LTL8

For the validation of SCENARIO1 and SCENARIO2, one needs (1) to replay them by executing the corresponding events, and (2) to check the desired behavior afterwards. To generate those scenarios, the modeler could animate the model, encode postconditions, and use the traces as regression tests afterwards. This is realized in TR1 and TR2 respectively. Afterwards, one could then define two respective VOs validating both VTs as shown in VO12 and VO13.

TR1/TrafficLight/TR: \[\text{INITIALISATION} < tl_{cars} = \text{red} \land tl_{peds} = \text{red} >, cars_{ry} < tl_{cars} = \text{redyellow} \land tl_{peds} = \text{red} >, cars_{g} < tl_{cars} = \text{green} \land tl_{peds} = \text{red} >, cars_{y} < tl_{cars} = \text{yellow} \land tl_{peds} = \text{red} >, cars_{r} < tl_{cars} = \text{red} \land tl_{peds} = \text{red} >\]

VO12: TR1

TR2/TrafficLight/TR: \[\text{INITIALISATION} < tl_{peds} = \text{red} \land tl_{cars} = \text{red} >, peds_{g} < tl_{peds} = \text{green} \land tl_{cars} = \text{red} >, peds_{r} < tl_{peds} = \text{red} \land tl_{cars} = \text{red} >\]

VO13: TR2

As mentioned before, a domain expert could be interested in sending commands only, without taking the traffic lights’ colors into account. The diagram portrayed in PRC1 (Figure 3) could then be validated by projecting the state space on queuedCmd for inspection (formalized in SPRJ1) after applying explicit-state model checking to cover the complete state space (realized in MC4). Both tasks are composed in VO14 sequentially as SPRJ1 depends on MC4.

MC4/TrafficLight/MC: <FIN>
SPRJ1/TrafficLight_Ref/SPRJ: queuedCmd, \( S_{queuedCmd} = \{ \text{cmd\_none}, \text{cmd\_cars\_ry}, \text{cmd\_cars\_y}, \text{cmd\_cars\_g}, \text{cmd\_cars\_r}, \text{cmd\_peds\_r}, \text{cmd\_peds\_g} \} \wedge \\
T_{queuedCmd} = \{ (\text{INITIALISATION}, \text{cmd\_none}) \} \cup \\
\{ \text{cmd\_none} \mapsto \text{Send\_cmd(cars\_r)} \mapsto \text{cmd\_cars\_r}, \text{cmd\_none} \mapsto \text{Send\_cmd(cars\_ry)} \mapsto \text{cmd\_cars\_ry}, \text{cmd\_none} \mapsto \text{Send\_cmd(cars\_g)} \mapsto \text{cmd\_cars\_g}, \text{cmd\_none} \mapsto \text{Send\_cmd(cars\_y)} \mapsto \text{cmd\_cars\_y}, \text{cmd\_none} \mapsto \text{Send\_cmd(peds\_g)} \mapsto \text{cmd\_peds\_g}, \text{cmd\_none} \mapsto \text{Send\_cmd(peds\_r)} \mapsto \text{cmd\_peds\_r} \} \cup \\
\{ \text{cmd\_cars\_r} \mapsto \text{Reject\_cmd} \mapsto \text{cmd\_none}, \text{cmd\_cars\_ry} \mapsto \text{Reject\_cmd} \mapsto \text{cmd\_none}, \text{cmd\_cars\_g} \mapsto \text{Reject\_cmd} \mapsto \text{cmd\_none}, \text{cmd\_cars\_y} \mapsto \text{Reject\_cmd} \mapsto \text{cmd\_none}, \text{cmd\_peds\_g} \mapsto \text{Reject\_cmd} \mapsto \text{cmd\_none}, \text{cmd\_peds\_r} \mapsto \text{Reject\_cmd} \mapsto \text{cmd\_none} \} \cup \\
\{ \text{cmd\_cars\_r} \mapsto \text{cars\_r} \mapsto \text{cmd\_none}, \text{cmd\_cars\_ry} \mapsto \text{cars\_ry} \mapsto \text{cmd\_none}, \text{cmd\_cars\_g} \mapsto \text{cars\_g} \mapsto \text{cmd\_none}, \text{cmd\_cars\_y} \mapsto \text{cars\_y} \mapsto \text{cmd\_none}, \text{cmd\_peds\_g} \mapsto \text{peds\_g} \mapsto \text{cmd\_none}, \text{cmd\_peds\_r} \mapsto \text{peds\_r} \mapsto \text{cmd\_none} \} \\

VO14: MC4:SPRJ1

When validating PROB-TIM1, the modeler could apply hypothesis testing, or estimation of probability. Here, we will demonstrate the validation of this requirement by applying hypothesis testing (see HT1). The configuration to define a hypothesis depends on the tool. In the context of ProB, in particular SimB, the VTs’ parameters are represented as \((H, \alpha)\) with the hypothesis \(H\), and the significance level \(\alpha\). Again, the hypothesis \(H\) is represented as \((P_{start}, P_{end}, P_{prop}, T_{procedure}, Pr)\) containing the starting condition \(P_{start}\), the ending condition \(P_{end}\), the checked property \(P_{prop}\), the test procedure \(T_{procedure}\) and the probability \(Pr\). Here, the starting condition states that both traffic lights are red, the ending condition describes that 30 seconds have passed, the property to be checked is that the cars’ traffic light eventually turns green, the kind of the hypothesis test is left-tailed, and the desired probability is 80 %. Again, the significance level is defined as 1%. Within the simulation configuration, we define 10000 runs to be simulated. Validating PROB-TIM2 is done similarly to PROB-TIM1 with the main difference that the property to be checked states that the pedestrians’ traffic light is green in the final state instead of the cars’ traffic light (realized by HT2). The respective VOs validating both VTs are shown in VO15 and VO16.

HT1/TrafficLight, TrafficLight_Sim/HT: (\langle PRED, tl\_cars = \text{red} \land tl\_peds = \text{red} \rangle, \langle TIME, 30000 \rangle, \langle EVENTUALLY, tl\_cars = \text{green} \rangle, LEFT\_TAILED, 0.8), 0.01
In the following, we are going to demonstrate the validation of non-functional requirements.

As described before COV1, COV2, and COV3 are coverage criteria for the validation of SCENARIO1 and SCENARIO2.

In order to validate COV1, the modeler needs to inspect the variable coverage table after running TR1 and TR2 which validates SCENARIO1 and SCENARIO2 respectively. Here, it is necessary to check whether the values for tl_cars and tl_peds are equal to 4 and 2 respectively (realized in VCT1).

\[
\text{VCT1/TrafficLight/VCT: } R_{\text{vct}}(\text{tl_cars}) = 4 \land R_{\text{vct}}(\text{tl_peds}) = 2
\]

Similar to the validation of COV1, the modeler must also run TR1 and TR2 validating SCENARIO1 and SCENARIO2 before validating COV2. It is then necessary to inspect the operation coverage table manually, to check whether all events have been covered (realized by OCT1).

\[
\text{OCT1/TrafficLight/OCT: } \{(\text{cars}_r, \text{COVERED}), (\text{cars}_y, \text{COVERED}), (\text{cars}_y, \text{COVERED}), (\text{cars}_r, \text{COVERED}), (\text{peds}_r, \text{COVERED}), (\text{peds}_g, \text{COVERED})\} = R_{\text{oct}}
\]

COV3 describes the desired statistics for the number of states and transitions after running TR1 and TR2, validating SCENARIO1 and SCENARIO2. As SCENARIO1 and SCENARIO2 should also cover the whole state space, the statistics are also expected to be equal to the statistics when applying explicit-state model checking. To check this coverage criterion, the modeler has to run STAT1 afterwards. Furthermore, STAT1 has to be checked
after running explicit-state model checking to cover the whole state space as shown in MC4.

\[
\text{STAT1}/\text{TrafficLight}/\text{STAT}: \quad R_{\text{spstat}}(\text{"Number of States"}) = 6 \ \land \\
R_{\text{spstat}}(\text{"Number of Transitions"}) = 7
\]

\[
\text{VO19}: \quad ((\text{TR1} \land \text{TR2}); \text{STAT1}) \land (\text{MC4};\text{STAT1})
\]

The requirements \text{STRUCT1} and \text{STRUCT2} desire \text{tl.cars} and \text{tl.peds} to be written by certain events. This can be validated by the respective VOs \text{VO20} and \text{VO21}, running the respective tasks \text{RWM1} and \text{RWM2}. Those VTs has to be checked by inspecting the read/write matrix manually.

\[
\text{RWM1}/\text{TrafficLight}/\text{RWM}: \quad R_{\text{rwm}}\{\text{WRITE}\} \sim \{\text{tl.cars}\} = \{\text{cars}_\text{ry}, \text{cars}_\text{g}, \text{cars}_\text{y}, \text{cars}_\text{r}\}
\]

\[
\text{VO20}: \quad \text{RWM1}
\]

\[
\text{RWM2}/\text{TrafficLight}/\text{RWM}: \quad R_{\text{rwm}}\{\text{WRITE}\} \sim \{\text{tl.peds}\} = \{\text{peds}_\text{g}, \text{peds}_\text{r}\}
\]

\[
\text{VO21}: \quad \text{RWM2}
\]

Again, ensuring that there are no vacuous parts in the invariant and guards of the Traffic Light model (\text{STRUCT3}) can be checked by the VTs shown in \text{VAP1} and \text{VAP2}. The corresponding VO applying both tasks is realized in \text{VO22}.

\[
\text{VAP1}/\text{TrafficLight}/\text{VAP}: \quad \text{INV}
\]

\[
\text{VAP2}/\text{TrafficLight}/\text{VAP}: \quad \text{GRD}
\]

\[
\text{VO22}: \quad \text{VAP1} \land \text{VAP2}
\]

\text{STRUCT4} describes how events enable each other. This can be translated to task \text{ED1}. The validation of \text{ED1} is done by \text{VO23}. 

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For the validation of \textsc{struc5} and \textsc{struc6}, one could apply test case generation. In order to validate \textsc{struc5}, test case generation covering all operations could be applied (realized by \textsc{oc1}). Again, MCDC coverage test case generation is suitable to validate \textsc{struc6} (see \textsc{mcdc1}). Afterwards, \textsc{struc5} and \textsc{struc6} are validated by \textsc{vo24} and \textsc{vo25} respectively.

\begin{verbatim}
 VO23: ED1

 For the validation of \textsc{struc5} and \textsc{struc6}, one could apply test case generation. In order to validate \textsc{struc5}, test case generation covering all operations could be applied (realized by \textsc{oc1}). Again, MCDC coverage test case generation is suitable to validate \textsc{struc6} (see \textsc{mcdc1}). Afterwards, \textsc{struc5} and \textsc{struc6} are validated by \textsc{vo24} and \textsc{vo25} respectively.
\end{verbatim}

\begin{verbatim}
 VO24: OC1

 Other VOs to validate requirements

 Using the previous VOs, all requirements for the traffic light model have already been covered. In the following, we will now demonstrate VTs that have not been used yet. Some VTs will be demonstrated on existing requirements of the Traffic Light example. In contrast, there will also be VTs that will be demonstrated on new requirements, or even other models.

 Instead of validating \textsc{safl} by checking \textsc{mc1}, it would also be possible to apply symbolic model checking. The corresponding VO, applying symbolic model checking (see \textsc{smc1}) is shown in \textsc{vo26}.
\end{verbatim}

\begin{verbatim}
 VO26: SMC1

 Other VOs to validate requirements

 Using the previous VOs, all requirements for the traffic light model have already been covered. In the following, we will now demonstrate VTs that have not been used yet. Some VTs will be demonstrated on existing requirements of the Traffic Light example. In contrast, there will also be VTs that will be demonstrated on new requirements, or even other models.

 Instead of validating \textsc{safl} by checking \textsc{mc1}, it would also be possible to apply symbolic model checking. The corresponding VO, applying symbolic model checking (see \textsc{smc1}) is shown in \textsc{vo26}.
\end{verbatim}

\begin{verbatim}
 Another possibility to validate \textsc{safl} could be done by proving multiple proof obligations. Here, it would be necessary to generate a PO for the initialization, and for each event checking whether it preserves the invariant describing
\end{verbatim}
SAF1. As result, this would lead to seven POs (denoted as PO1 - PO7) being generated, one for each operation, to validate SAF1. In order to fully validate SAF1, it is thus necessary to prove all POs as realized in VO27. PO1 shows the proof obligation (also used as validation task) for invariant preservation of the property describing SAF1 from the event cars_ry. Note that proving POs might need some human interaction.

\[
\begin{align*}
\text{PO1/TrafficLight/PO: } & \text{tl}_c \in \text{colors, tl}_p \in \{\text{red, green}\}, \text{tl}_p = \text{red} \\
& \text{or } \text{tl}_c = \text{red, tl}_p = \text{red, tl}_p = \text{red, tl}_c = \text{redyellow, tl}_p = \text{tl}_p \vdash \text{tl}_p = \text{red or tl}_c = \text{red}
\end{align*}
\]

\[
\text{VO27: } \text{PO1} \land \text{PO2} \land \ldots \land \text{PO7}
\]

As an alternative to STAT1, one could also inspect the state space visualization (realized by SVIS1) after running TR1 and TR2. The result could then be checked against the coverage after applying MC4. Both are realized in VO28. As the state space can grow very fast, it is often better in practice to inspect the state space statistics after checking MC4 as realized by STAT1.

\[
\begin{align*}
\text{SVIS1/TrafficLight/SVIS: } & \text{card}(Z_{\text{vis}}) = 6 \land \text{card}(T_{\text{vis}}) = 7
\end{align*}
\]

\[
\text{VO28: } ((\text{TR1} \land \text{TR2}); \text{SVIS1}) \land (\text{MC4}; \text{SVIS1})
\]

As an alternative to LTL5.1 and LTL7.1, it would also be possible to apply CTL model checking to expect a positive result. The VOs applying the respective tasks CTL1 and CTL2 are shown in VO29 and VO30.

\[
\begin{align*}
\text{CTL1/TrafficLight/CTL: } & \text{EF}\{\text{tl}_c \neq \text{red}\}, \text{SUCCESS}
\end{align*}
\]

\[
\text{VO29: CTL1}
\]

\[
\begin{align*}
\text{CTL2/TrafficLight/CTL: } & \text{EF}\{\text{tl}_p \neq \text{red}\}, \text{SUCCESS}
\end{align*}
\]

\[
\text{VO30: CTL2}
\]

Instead of applying hypothesis testing, it would also be possible to validate PROB-TIM1 by estimating the probability. The configuration for the check
also depends on the tool. Similar to hypothesis testing, the parameters contain the starting condition, the ending condition, the property to be checked, the kind of estimation checking, and the desired probability. The only difference is the $\delta$ value which is used instead of the $\alpha$ value. The corresponding VO is shown in VO31, validating the corresponding task EOP1.

EOP1/TrafficLight, TrafficLight_Sim/EOP: 1000000, (<PRED, tl_cars = red ∧ tl_peds = red>, <TIME, 30000>, <EVENTUALLY, tl_cars = green>, LEFT_TAILED, 0.8), 0.01

VO31: EOP1

Now, we will introduce a new requirement to demonstrate the VO for probabilistic/statistical model checking:

PROB1: Whenever both traffic lights are red, the pedestrians’ traffic light will turn green with a probability of 50% next.

In order to apply probabilistic/statistical model checking, the modeler has to encode a markov chain as well. So, the demonstration of the corresponding VO is the only one that is not demonstrated using the B method and ProB. An encoding of the Traffic Light model in PRISM is shown in Listing 3. This is also the context for the VT PSMC1. Here, the probability to choose between the cars’ cycle and the pedestrians’ cycle is defined as 50% for each.

```
mdp module TrafficLight_PRISM
  tl_cars : [0..3] init 0;
  tl_peds : [0..3] init 0;

  [] tl_cars=0 & tl_peds = 0 -> 0.5:(tl_cars’=1) + 0.5:(tl_peds’=2);
  [] tl_cars=1 -> (tl_cars’ = 2);
  [] tl_cars=2 -> (tl_cars’ = 3);
  [] tl_cars=3 -> (tl_cars’ = 0);
  [] tl_peds=2 -> (tl_peds’ = 0);
endmodule
```

Listing 3: Traffic Light in PRISM

Validating PROB1 is then done by checking VO32, validating PSMC1 with PCTL formula.

PSMC1/TrafficLight_PRISM/PSMC: P>0.9999[¬(true U ¬((tl_cars = 0 ∧ tl_peds = 0) =⇒ (P>0.49 [ X (tl_peds = 2) ] ∧ P<0.51 [ X (tl_peds = 2) ]))))], SUCCESS
**PROB1** could also be validated by inspecting the simulation statistics (realized in **SISTAT1**). The corresponding VO is shown in **VO33**.

**SISTAT1**/TrafficLight, TrafficLight_Sim/SISTAT: 10000, \( <\text{PRED}, 1=1>, <\text{STEPS}, 100>, R_{\text{sistat}}(\text{enabled} \rightarrow \text{peds.g})/R_{\text{sistat}}(\text{executed} \rightarrow \text{peds.g}) \in [0.49, 0.51] \)

**VO33**: **SISTAT1**

As the Traffic Light model contains variables from the type **colors** only, it is not possible to inspect minimum and maximum values. Let us consider a lift moving between the ground level and the 100th level. Furthermore, assume that the level is modeled by a variable **level**. Consider a scenario shown in **SCENARIO-LIFT**.

**SCENARIO-LIFT**: In the beginning, the lift is located at the ground level. It then moves floor by floor until it reaches the third level.

After validating **SCENARIO-LIFT**, i.e., after re-playing the scenario realized by a task **TR-LIFT**, it is expected that the lift has moved between the ground floor and the third level. The corresponding requirement is shown in **COV-LIFT**.

**COV-LIFT**: After validating **SCENARIO-LIFT**, it is expected that the lift has moved between the ground floor and the third level.

**COV-LIFT** could then be validated by **VO-LIFT**, which inspects the minimum and maximum value as shown in **MMV-LIFT** after running **TR-LIFT**.

**MMV-LIFT**/Lift/MMV: \( \min(R_{\text{mmv}}(\text{level})) = 0 \land \max(R_{\text{mmv}}(\text{level})) = 3 \)

Finally, we will also show a VO, applying model checking to search for a goal, which is used as an initial state to run trace replay. This will be demonstrated in an automotive case study [63]. Consider the scenario shown in **SCENARIO-AUTO**.
SCENARIO-AUTO:
Assuming that the engine is turned on, and the blinker is in position Downward. After 500 ms, the lights on the left-hand side turn on with an intensity of 100. When passing another 500 ms, the lights on the left-hand side turn off. Both events are repeated in the same order one more time. While the lights on the left-hand side are blinking, those on the right-hand side are always turned off.

First, the assumption of the scenario (engine turned on, and blinker in position Downward) is validated by finding a state from which the other events of the scenario are executed. This is realized by the explicit-state model check MC-AUTO. Outgoing from the state that should be found, the rest of the scenario is then validated via trace replay which is realized by TR-AUTO.

\[
\text{MC-AUTO/PitmanController\_Time\_MC\_v4/MC:} \\
\langle \text{GOAL, engineOn = TRUE } \land \text{ pitmanArmUp\_Down = Downward} \rangle
\]

\[
\text{TR-AUTO/PitmanController\_Time\_MC\_v4/TR:} \\
\langle \text{RTIME\_Blinker\_On(delta=500) < blinkLeft = 100, blinkRight=0>}, \text{RTIME\_Blinker\_Off(delta=500) < blinkLeft = 0, blinkRight=0>}, \text{RTIME\_Blinker\_On(delta=500) < blinkLeft = 100, blinkRight=0>}, \text{RTIME\_Blinker\_Off(delta=500) < blinkLeft = 0, blinkRight=0>}\rangle
\]

VO-AUTO: MC-AUTO; TR-AUTO

Traceability of Requirements Figure [a] shows a taxonomy of a subset of requirements (FUN1, FUN5, SCENARIO1, SCENARIO2, COV1, PRC1), as well as VO, s and VTs validating them. Based on this taxonomy, we will demonstrate how possible error sources could be traced when a VO fails. For example, assuming that VO1 has failed, the possible error sources could be LTL1, the requirement FUN1, or the model. Similarly, VO5 is traced to LTL5.1, LTL5.2, FUN5, or the model. Again, VO14 is traced to SPRJ1, MC4, PRC1, or the model. While VO12 and VO13 are traced to TR1 and TR2, and thus also SCENARIO1 and SCENARIO2 respectively, tracing VO to VTs and requirements is more complicated for VO18. Here, it is necessary to determine which parts of the VO has failed. In the case that only OCT fails, it means that the set of scenarios might be incomplete. In contrast, TR3 and TR4 are traced via VO12 and VO13 respectively. This means that VO18 could have failed because of the failure of VO12 or VO13.

In the case that an error is found, it is also important (1) to track contradicting requirements, and (2) to avoid introducing new bugs when trying to fix this error. For example, fixing SCENARIO1 in the model might cause other
requirements to fail. The modeler must then check, whether the SCENARIO01 contradicts other requirements, or whether there are bugs introduced when the model evolves.

Figure 4: Taxonomy with Requirements FUN1, FUN5, SCENARIO01, SCENARIO02, COV1, PRC1, and corresponding VTs, and VOs validating them
A Glossary

State The state of a (software) system is represented by the values of its variables (and constants).

Operation An operation is a term that is well-known from the formal B method. Analogous terms are, e.g., events or actions. It consists of a guard, several effects, and optionally input and return parameters. A guard is a predicate corresponding to an operation which is true when the operation is enabled. When executing the operation, the effects are applied to the current state, modifying it to the succeeding state.

Transition A transition is labeled with an operation (and its parameters), and defined between two states $s_1$ and $s_2$ under the following condition: The operation together with its parameters is enabled in $s_1$, and executing the operation with the parameters modifies $s_1$ resulting in $s_2$.

State Space A state space shows all possible executions of the system. It consists of a set of states and transitions between them.

Trace A trace is a list of transitions describing a path through the state space.

Scenario A scenario is a (high-level) sequence of events (written in natural language) that describes certain desired behavior patterns.

Differences between Scenario and Traces While researching literature it became apparent that the terms of trace and scenario have different meanings in the formal methods community. Scenarios have also different meanings depending on the domain and context they are used in [50, 78, 64, 83]. In the referenced paper it is somewhat agreed that a scenario describes a desired behavior. For software development, a scenario is then often expressed in a non-ambiguous DSL like Gherkin [105]. In software engineering, there is the sentiment that traces are a realisation of a scenario, shown for example in [72]. Depending on the underlying formalism a scenario can therefore have multiple traces that satisfy it.

Verification Verification checks whether a model meets its specification. So, here we ask the question: Are we building the software correctly?

Validation Validation checks whether a model meets the stakeholder’s requirements. So the main question is: Are we building the right software?
Validation Obligation  A validation obligation (VO) is composed of (multiple) validation tasks (VT) associated with a model to check its compliance with a requirement. Thus, validating a requirement succeeds if all associated VOs yield successful results. Formally, a VO is annotated with an id, and consists of a validation expression (written as: \text{VO}_{\text{id}} : \text{VO}_{\text{expression}}).

Validation Expression  The validation expression (VE) consists of operations on the associated validation tasks. It is part of the validation obligation.

Validation Technique  A validation technique is a technique to validate a requirement. For example, one could validate a requirement describing a temporal property by LTL model checking. In this case, LTL model checking is the validation technique.

Validation Task  A validation task (VT) is identified with an identifier, and consists of a validation technique that is applied with the given validation parameters to the corresponding context. Executing a VT possibly modifies the internal state of the validation tool, e.g., consisting of the currently explored state space, and the current trace. The notation for a VT is as follows: \text{VT}_{\text{id}}/\text{VT}_{\text{context}}/\text{VT}_{\text{technique}}: \text{VT}_{\text{parameters}}
B Traffic Light Refinement

```
MACHINE TrafficLight2
SETS colors = {red, redyellow, yellow, green};
COMMANDS = {cmd_cars_ry, cmd_cars_y, cmd_cars_g, 
             cmd_cars_r, cmd_peds_r, cmd_peds_g, cmd_none}
VARIABLES tl_cars, tl_peds
INVARIANT tl_cars : colors & tl_peds : {red, green} & 
             (tl_peds = red or tl_cars = red)
INITIALISATION tl_cars := red || tl_peds := red
OPERATIONS
Send_cmd(cmd) = SELECT cmd : COMMANDS THEN skip END;
Reject_cmd = skip;
cars_ry = SELECT tl_cars = red & tl_peds = red THEN tl_cars := redyellow END;
cars_y = SELECT tl_cars = green THEN tl_cars := yellow END;
cars_g = SELECT tl_cars = redyellow THEN tl_cars := green END;
cars_r = SELECT tl_cars = yellow THEN tl_cars := red END;
peds_r = SELECT tl_peds = green THEN tl_peds := red END;
peds_g = SELECT tl_cars = red & tl_peds = red THEN tl_peds := green END
END
```

Listing 4: Abstract Traffic Light

```
REFINEMENT TrafficLightCommand_Ref REFINES TrafficLight2
VARIABLES tl_cars, tl_peds, queuedCmd
INVARIANTS queuedCmd : COMMANDS
INITIALISATION tl_cars := red || tl_peds := red || queuedCmd := cmd_none
OPERATIONS
Send_cmd(cmd) = SELECT cmd : COMMANDS & cmd /= cmd_none & queuedCmd = cmd_none 
THEN 
    queuedCmd := cmd 
END;
Reject_cmd = 
    SELECT queuedCmd /= cmd_none 
THEN 
    queuedCmd := cmd_none 
END;
cars_ry = 
    SELECT 
    tl_cars = red & tl_peds = red & queuedCmd = cmd_cars_ry 
THEN 
    tl_cars := redyellow || 
    queuedCmd := cmd_none 
END;
cars_y = 
    SELECT 
    tl_cars = green & queuedCmd = cmd_cars_y 
THEN 
    tl_cars := yellow || 
    queuedCmd := cmd_none 
END;
cars_g = 
    SELECT 
    tl_cars = redyellow & queuedCmd = cmd_cars_g 
THEN 
    tl_cars := green || 
    queuedCmd := cmd_none 
END;
cars_r = 
```
SELECT
tl_cars = yellow & queuedCmd = cmd_cars_r
THEN
tl_cars := red ||
queuedCmd := cmd_none
END;

peds_r =
SELECT
tl_peds = green & queuedCmd = cmd_peds_r
THEN
tl_peds := red ||
queuedCmd := cmd_none
END;

peds_g =
SELECT
tl_cars = red & tl_peds = red & queuedCmd = cmd_peds_g
THEN
tl_peds := green ||
queuedCmd := cmd_none
END
C Overview VT Examples

Trace Replay VT:

\[
\text{TR1}/\text{TrafficLight/TR: [INITIALISATION}\ <t_l\text{cars} = \text{red} \land t_l\text{peds} = \text{red}>, c_{ars}_{ry} <t_l\text{cars} = \text{redyellow} \land t_l\text{peds} = \text{red}>, c_{ars}_{r} <t_l\text{cars} = \text{green} \land t_l\text{peds} = \text{red}>, c_{ars}_{y} <t_l\text{cars} = \text{yellow} \land t_l\text{peds} = \text{red}>, c_{ars}_{r} <t_l\text{cars} = \text{red} \land t_l\text{peds} = \text{red}>]
\]

Operation Coverage Test Case Generation VT:

\[
\text{OC1}/\text{TrafficLight/OC:}[c_{ars}_{r}, c_{ars}_{ry}, c_{ars}_{g}, c_{ars}_{r}, p_{eds}_{g}, p_{eds}_{r}]
\]

MC/DC Coverage Test Case Generation VT:

\[
\text{MCDC1}/\text{TrafficLight/MCDC:2}
\]

Hypothesis Testing VT:

\[
\text{HT1}/\text{TrafficLight, TrafficLight Sim/HT: (}<\text{PRED, } t_l\text{cars} = \text{red} \land t_l\text{peds} = \text{red}>, <\text{TIME, 30000}>, <\text{EVENTUALLY, } t_l\text{cars} = \text{green}>, \text{LEFT TAILED}, 0.8), 0.01
\]

Estimation of Probability VT:

\[
\text{EOP1}/\text{TrafficLight, TrafficLight Sim/EOP: (}<\text{PRED, } t_l\text{cars} = \text{red} \land t_l\text{peds} = \text{red}>, <\text{TIME, 30000}>, <\text{EVENTUALLY, } t_l\text{cars} = \text{green}>, \text{LEFT TAILED}, 0.8), 0.01
\]

Simulation Statistics VT:

\[
\text{SISTAT1}/\text{TrafficLight, TrafficLight Sim/SISTAT: <PRED, 1=1>, <STEPS, 100>, } R_{sistat} (\text{enabled } \Rightarrow \text{cars}_{ry})/R_{sistat} (\text{executed } \Rightarrow \text{cars}_{ry}) \in [0.49, 0.51]
\]

Explicit-State Model Checking VT:

\[
\text{MC1}/\text{TrafficLight/MC: <INV, } t_l\text{cars} = \text{red or } t_l\text{peds} = \text{red}>
\]

LTL Model Checking VT:
LTL1/TrafficLight/LTL: \{tl\_cars = red \land tl\_peds = red\}, SUCCESS

CTL Model Checking VT:

CTL1/TrafficLight/CTL: EF{tl\_cars \neq red}, SUCCESS

Probabilistic/Statistical Model Checking VT:

PSMC1/TrafficLight_PRISM/PSMC: P>0.9999\sim(\text{true } U \sim((tl\_cars = 0 \land tl\_peds = 0) \implies (P>0.49 [ X (tl\_peds = 2) ] \land P<0.51 [ X (tl\_peds = 2) ]))\)), SUCCESS

Symbolic Model Checking VT:

SMC1/TrafficLight/SMC: <INV, tl\_cars = red or tl\_peds = red>

Proving VT:

PO1/TrafficLight/PO: tl\_cars \in \text{colors}, tl\_peds \in \{\text{red, green}\}, tl\_peds = \text{red or tl\_cars = red, tl\_cars = red, tl\_peds = red}, tl\_cars = \text{redyellow}, tl\_peds = \text{tl\_peds = red or tl\_cars' = red or tl\_cars' = red}

Variable Coverage Table VT:

VCT1/TrafficLight/VCT: R_{vct}(tl\_cars) = 4 \land R_{vct}(tl\_peds) = 2

Min/Max Values VT:

MMV-LIFT/Lift/MMV: \text{min}(R_{mmv}(\text{level})) = 0 \land \text{max}(R_{mmv}(\text{level})) = 3

Operation Coverage Table VT:

OCT1/TrafficLight/OCT:
\{(\text{cars\_y, COVERED), (cars\_r, COVERED), (cars\_y, COVERED), (cars\_r, COVERED), (peds\_r, COVERED), (peds\_g, COVERED)}\} = R_{oct}

Read/Write Matrix VT:
RWM1/TrafficLight/RWM: \( R_{\text{rwrm}} = \{\{\text{WRITE}\}\} \sim \{\text{tl_cars}\} = \{\text{cars}_{\text{ry}}, \text{cars}_{\text{g}}, \text{cars}_{\text{y}}, \text{cars}_{\text{r}}\} \)

Enabling Diagram VT:

ED1/TrafficLight/ED:
\[
\{(\text{cars}_{\text{ry}}, \text{cars}_{\text{g}}), (\text{cars}_{\text{g}}, \text{cars}_{\text{y}}), (\text{cars}_{\text{y}}, \text{cars}_{\text{r}}), (\text{cars}_{\text{r}}, \text{cars}_{\text{ry}}),
(\text{cars}_{\text{r}}, \text{peds}_{\text{g}}), (\text{peds}_{\text{g}}, \text{peds}_{\text{r}}), (\text{peds}_{\text{r}}, \text{peds}_{\text{g}}), (\text{peds}_{\text{r}}, \text{cars}_{\text{ry}})\} = R_{\text{ed}}.
\]

Vacuous Parts VT:

VAP1/TrafficLight/VAP: INV

State Space Visualization VT:

SVIS1/TrafficLight/SVIS:
\[\text{card}(Z_{\text{svis}}) = 6 \land \text{card}(T_{\text{svis}}) = 7\]

State Space Projection VT:

SPRJ1/TrafficLight_Ref/SPRJ: \(\text{queuedCmd}, S_{\text{queuedCmd}} = \{<\text{undefined}>, \text{cmd}_{\text{none}}, \text{cmd}_{\text{cars}_{\text{ry}}}, \text{cmd}_{\text{cars}_{\text{y}}}, \text{cmd}_{\text{cars}_{\text{g}}}, \text{cmd}_{\text{cars}_{\text{r}}}, \text{cmd}_{\text{peds}_{\text{r}}}, \text{cmd}_{\text{peds}_{\text{g}}}\} \land
\]
\[
T_{\text{queuedCmd}} = \{(<\text{undefined}>, \text{INITIALISATION}, \text{cmd}_{\text{none}})\} \cup
\{\text{cmd}_{\text{none}} \mapsto \text{Send}_{\text{cmd}}(\text{cars}_{\text{r}}) \mapsto \text{cmd}_{\text{cars}_{\text{r}}}, \text{cmd}_{\text{none}} \mapsto \text{Send}_{\text{cmd}}(\text{cars}_{\text{ry}}) \mapsto \text{cmd}_{\text{cars}_{\text{ry}}}, \text{cmd}_{\text{none}} \mapsto \text{Send}_{\text{cmd}}(\text{cars}_{\text{g}}) \mapsto \text{cmd}_{\text{cars}_{\text{g}}}, \text{cmd}_{\text{none}} \mapsto \text{Send}_{\text{cmd}}(\text{cars}_{\text{y}}) \mapsto \text{cmd}_{\text{cars}_{\text{y}}}, \text{cmd}_{\text{none}} \mapsto \text{Send}_{\text{cmd}}(\text{peds}_{\text{g}}) \mapsto \text{cmd}_{\text{peds}_{\text{g}}}, \text{cmd}_{\text{none}} \mapsto \text{Send}_{\text{cmd}}(\text{peds}_{\text{r}}) \mapsto \text{cmd}_{\text{peds}_{\text{r}}}\} \cup
\{\text{cmd}_{\text{cars}_{\text{r}}} \mapsto \text{Reject}_{\text{cmd}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{cars}_{\text{ry}}} \mapsto \text{Reject}_{\text{cmd}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{cars}_{\text{y}}} \mapsto \text{Reject}_{\text{cmd}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{cars}_{\text{g}}} \mapsto \text{Reject}_{\text{cmd}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{peds}_{\text{r}}} \mapsto \text{Reject}_{\text{cmd}} \mapsto \text{cmd}_{\text{none}}\} \cup
\{\text{cmd}_{\text{cars}_{\text{r}}} \mapsto \text{cars}_{\text{r}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{cars}_{\text{ry}}} \mapsto \text{cars}_{\text{ry}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{cars}_{\text{g}}} \mapsto \text{cars}_{\text{g}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{cars}_{\text{y}}} \mapsto \text{cars}_{\text{y}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{peds}_{\text{g}}} \mapsto \text{peds}_{\text{g}} \mapsto \text{cmd}_{\text{none}}, \text{cmd}_{\text{peds}_{\text{r}}} \mapsto \text{peds}_{\text{r}} \mapsto \text{cmd}_{\text{none}}\}\]

State Space Statistics VT:

40
D Published Papers

In the following, we list the papers that are published in the context of D 1.1. of the IVOIRE project:

- Atif Mashkoor, Michael Leuschel, Alexander Egyed. Validation Obligations: A Novel Approach to Check Compliance between Requirements and their Formal Specification [70]
- Fabian Vu, Michael Leuschel, Atif Mashkoor. Validation of Formal Models by Timed Probabilistic Simulation [101]
- Atif Mashkoor, Alexander Egyed. Evaluating the alignment of sequence diagrams with system behavior [67]
- Jens Bendisposto, David Geleßus, Yumiko Jansing, Michael Leuschel, Antonia Pütz, Fabian Vu, Michelle Werth. ProB2-UI: A Java-Based User Interface for ProB [10] (extended in context of IVOIRE)

E Changes History

Version 1.0.0: Initial Version

Version 1.1.0:
- Introduction updated
- Classification of Requirements - now Section 2 instead of Section 4
- "Overlap between Validation and Verification" renamed to "Verification and Validation"
- "Verification and Validation" updated
- "Comparison with Proof Obligations" (Section 2.1) removed - now discussed in Section 1
- Validation Obligations Approach - now Section 4 instead of Section 2
- Section 2.4. ("Refinement") and Section 2.5. ("Refactoring") - merged to "Refinement and Refactoring" and moved to Section 4.1.
- Section 5 ("Validation Techniques and Validation Obligations") - now moved to Section 4.2. and renamed to "Validation Techniques and Tasks"
• Separate validation obligation and validation task

• Introduce definition for validation task in "Validation Techniques and Tasks"

• Introduce parallel (||) and sequential (;) composition for validation task

• Introduce Table 1 - showing overview of all validation tasks

• Remove mathematical formulations of validation tasks - now described in Table 1

• Remove Trace Refinement as validation task (originally Section 5.2.)

• Minor changes in Section 4.2. (originally Section 5.)

• Vacuous Guards/Invariants - not part of "Validation by Visualization, Statistics, and Metrics" anymore

• Introduce Section 4.3. ("Definition of Validation Obligation")

• Formal Definition of Validation Obligation updated

• Minor changes in Formulation of "Definition of Validation Obligation"

• Section 2.3 "Creating Validation Tasks" - now renamed to "Creating Validation Obligations" (Section 4.4.)

• Section 2.2. "Development" - now renamed to "VO-guided Workflow" and moved to Section 4.5.

• Remove Figure 2 in "VO-guided Workflow" (originally Section 2.2.)

• Section 6 "Demonstration of Validation Obligations" - now Section 5

• Minor changes in formulations in "Demonstration of Validation Obligations"

• Remove PRC1 in "Demonstration of Validation Obligations"

• Separation between validation task and validation obligation in "Demonstration of Validation Obligations" following the new definitions in Section 4.2. "Validation Techniques and Tasks" and Section 4.3. "Definition of Validation Obligation"

• Use parallel and sequential composition of validation task in VOs in "Demonstration of Validation Obligations"

• Remove TRF1 validating PRC1 in "Demonstration of Validation Obligations"
• Add and Explain Figure 3: "Taxonomy with Requirements FUN1, FUN5, SCENARIO1, SCENARIO2, COV1, PRC1, and corresponding VTs, and VOs validating them"

• Rename MMV1 to MMV-LIFT

• Minor changes in formulations in Glossary

• Update validation task in Glossary

• Add validation obligation, validation predicate, and validation function in Glossary

• Rename Appendix C "Overview VO Examples" to "Overview VT Examples"

• Rename VO to VT in "Overview VT Examples"

Version 1.2.0:

• Section 1 ("Introduction") updated

• Minor changes in Section 2.2 ("User Requirements and System Requirements")

• Section 3 ("Verification and Validation") updated, Figure 1 ("Role of Verification and Validation") added

• Minor changes in introduction of Section 4 ("Validation Obligations Approach")

• Minor changes in Section 4.1 ("Refinement and Refactoring")

• Split Section 4.2 ("Validation Techniques and Tasks") in Section 4.2 ("Definition of Validation Tasks") and Section 4.3 ("Classification of Validation Techniques")

• Table 1 moved to the end of Section 4.3 ("Classification of Validation Techniques")

• Table 1 changed (Number of Simulations for HT and EOP removed, Depth for OC and MCDC removed, style changed)

• Operators applied on VTs are now part of the VO, in particular, the VO<expression>, and not part of the VT anymore

• Minor changes in introduction of Section 4.3 ("Classification of Validation Techniques")

• Minor changes in "Validation by Visualization, Statistics, and Metrics" and "Code Generation for Validation" of Section 4.3 ("Classification of Validation Techniques")
• Minor change in textual definition of a VO (Section 4.4: "Definition of Validation Obligations")

• Replace VO_{predicate} by VO_{expression} in formal definition of a VO (Section 4.4: "Definition of Validation Obligations")

• Remove validation function (Section 4.4: "Definition of Validation Obligations")

• Adopt explanation of operations in VO_{expression} to formal definition

• Remove parallel operator (||) as it has the same semantics as the and operator (∧)

• Minor changes in Section 4.5 ("Creating Validation Obligations")

• Minor change/improvement in FUN8 in Section 5 ("Demonstration of Validation Obligations")

• Split Section 5 ("Demonstration of Validation Obligations") in two paragraphs: Requirements and Validation by VOs

• Remove validate predicate in Validation by VOs, Section 5 ("Demonstration of Validation Obligations")

• Replace & by ∨ in all VOs in Section 5 ("Demonstration of Validation Obligations") and Appendix

• Minor changes in text of Validation by VOs, Section 5 ("Demonstration of Validation Obligations")

• Remove <undefined> from SPRJ1

• Minor change in text for validation of PROB-TIM1, COV1, COV3, STRUC1, and STRUC2

• Change STRUC5 and STRUC6

• Remove depth in OC1 and MCDC1

• Minor change in SCENARIO-AUTO

• Split discussion with Figure 4 ("Taxonomy with Requirements FUN1, FUN5, SCENARIO1, SCENARIO2, COV1, PRC1, and corresponding VTs, and VOs validating them") to separate paragraph in Section 5: "Traceability of Requirements"

• Updated Figure 4 ("Taxonomy with Requirements FUN1, FUN5, SCENARIO1, SCENARIO2, COV1, PRC1, and corresponding VTs, and VOs validating them")

• More texts added in Section 5: "Traceability of Requirements"
• Remove Validation Function and Validation Predicate in Glossary

• Add Validation Expression in Glossary

• Replace Validation Predicate by Validation Expression in Validation Obligation in Glossary

• Minor changes in formulations in Glossary: validation task, scenario

• Remove Composed VTs in Appendix D ("Overview VT Examples")

• Appendix A ("Changes history") moved to Appendix E
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