Execution of Partial State Machine Models

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Abstract—The iterative and incremental nature of software development using models typically makes a model of a system incomplete (i.e., partial) until a more advanced and complete stage of development is reached. Existing model execution approaches (interpretation of models or code generation) do not support the execution of partial models. Supporting the execution of partial models at early stages of software development allows early detection of defects, which can be fixed more easily and at lower cost. This paper proposes a conceptual framework for the execution of partial models, which consists of three steps: static analysis, automatic refinement, and input-driven execution. First, a static analysis that respects the execution semantics of models is applied to detect problematic elements of models that cause problems for the execution. Second, using model transformation techniques, the models are refined automatically, mainly by adding decision points where missing information can be supplied. Third, refined models are executed, and when the execution reaches the decision points, it uses inputs obtained either interactively or by a script that captures how to deal with partial elements.

We created an execution engine called PMExec for the execution of partial models of UML-RT (i.e., a modeling language for the development of soft real-time systems) that embodies our proposed framework. We evaluated PMExec based on several use-cases that show that the static analysis, refinement, and application of user input can be carried out with reasonable performance, and that the overhead of approach, which is mostly due to the refinement and the increase in model complexity it causes, is manageable. We also discuss the properties of the refinement formally, and show how the refinement preserves the original behaviors of the model.

Index Terms—MDD, Model-level Debugging, Partial Models, Incomplete Models, Model Execution

1 INTRODUCTION

Model Driven Engineering (MDE) is a software development methodology that advocates the use of model for the description and development of systems [1]. These models can capture relevant concepts on a level of abstraction higher than source code, and thus can facilitate communication, automation, and reuse. In general, the level and form of the use of models varies greatly, from the use of models only for documentation and communication to the use of models for code generation and as the main software development artifacts rather than source code [2], [3], [4], [5]. While modeling is used in a range of industries such as telecom, automotive, aerospace, business, and military, its use for the development of Real-time Embedded (RTE) systems appears to be one of the most prevalent [6], [7], [8].

Over the last two decades, an impressive number of MDE tools and techniques for RTE systems have been introduced such as IBM RSARTE [9], ANSYS SCADE Suite [10], YAKINDU Statecharts [11], and AUTOFocus [12]. These tools provide a range of capabilities to simplify the development of RTE systems using models. E.g., the models can be executed, debugged, analyzed, visualized, and transformed. Our work concerns the execution of models, which is typically supported either by interpreting the models or by translating them into an existing programming language, often by code generation (translational execution) [13], [14].

The ability to execute models in some ways is an important capability of MDE tools because it enables many important quality assurance activities such as testing and debugging. However, while existing MDE tools offer good support for the execution of complete models, none of them make much effort to extend that support to models that are incomplete. For instance, a state machine model may be incomplete because the behaviour of a component or a composite state has not yet been specified, or the specification of a transition is missing or incomplete (due to, e.g., missing triggers or guards, or incomplete action code). Although these models might contain many executable parts and there might be great value in the ability to execute them, existing tools typically do not allow this. One reason is that code generation or build operations might fail. But, even if these steps succeed, the tools do not allow a ‘best effort’ treatment of partial models in which execution proceeds as far as possible and when it cannot proceed any further due missing information, then this missing information can be supplied manually or automatically to allow the execution to continue. Our work aims to enable this kind of best effort treatment.

Generally, the benefits of partial model execution can be classified as follows:

1) Facilitate design decisions. In very early stages of development, the ability to execute a partial model may help perform design space exploration, evaluate design alternatives and explore tradeoffs in a more efficient, focused fashion and without having to flesh out details that are irrelevant to the design decision, but required to achieve executability. The goal is to allow the model to be useful as early as possible and with a minimum of procedural or notational accidental complexity [15].

2) Facilitate validation and improvement of models. A basic tenet in software engineering is that development
should facilitate the early detection of bugs, because the cost of fixing a bug tends to increase with the amount of time that it goes unnoticed [16], [17], [18]. Agile development activities such as continuous testing are motivated by this observation. In the context of MDE, this means that developers should be able to carry out validation and debugging activities as early as possible and not only after additional effort has been invested to make the model complete. The ability to execute partial models is necessary to achieve this vision and a key prerequisite for making MDE more agile [15].

But, partial model execution can also help with the validation of large, complete models. In large MDE projects, the system can have hundreds of components [19], [20], much reducing the feasibility and practicality of system-wide validation activities, especially when execution requires code generation (e.g., as reported in [21] the code generation of large systems can take hours to complete). In these settings, unit testing of individual components is required. Each such component \( c \) is a partial model that typically is not executable in isolation. To achieve executability, the current state-of-the-art demands that \( c \) be completed by a harness that mocks or stubs out the parts of the system that \( c \) relies on. The creation of a suitable harness and connecting it to \( c \) can involve a significant amount of accidental complexity. Our approach facilitates unit testing, because the developer can focus on supplying appropriate information to \( c \) if and when \( c \) needs it.

3) **Facilitate collaborative, heterogeneous development.** MDE is often collaborative and different model parts can be owned by different, possibly geographically distributed, teams [22]. As a result, components may be out-of-date, incorrect, or unavailable which may affect the executability of any other components using them. Partial model execution can help protect the developers of a part of the system from these issues by allowing them to, e.g., perform validation without having to wait for a new version or attempt to make their part work with an old, out-dated version.

But, MDE can also be part of a larger, heterogeneous development process in which, e.g., the code generated from a model is integrated with other code that has been developed by a different team using a different process or tool, or been purchased from a vendor [22], [23]. Partial model execution can help here, too, because the model can be validated without having to obtain this additional code and integrate it with the model. According to surveys, the integration of MDE into industrial development processes can be challenging, especially when distributed development and interoperability with existing code or tools is required [3], [22], [23], [24]. Partial model execution can increase the flexibility of MDE and thus may help mitigate these problems and improve industrial adoption of MDE.

Despite the importance and benefits of the execution of partial models, no work has addressed the execution of partial models, to the best of our knowledge. Existing work in this context deals with partial models at design time, which allows for specification, analysis, verification, and transformation of partial models (e.g., [25], [26], [27], [28]). As mentioned, a possible approach to executing partial models is the simulation of missing components by techniques such as mocking or stubbing [29]. These solutions are mainly designed for unit testing, and have several deficiencies when used for the debugging of models: (1) They are not fully automated, and developers still need to do extra work to, e.g., create stubs for the missing components. (2) Often, they are applicable only at the component-level to simulate a component fully, while for debugging purposes, developers may need to simulate only parts of a component. (3) More importantly, while in the code-base development context, there are several mocking frameworks (e.g., Mockito, EasyMock, JMock, Opmock, etc.) that can be used to simulate components of a system [30], there is a lack of facilities, guidelines, and frameworks in the context of MDE to help to create mockers [31].

This work advances the state of the art in model-level execution and utilizing partial models by providing support for the execution of partial models. We propose a conceptual framework for the execution of partial models, which consists of three steps: **static analysis**, **automatic refinement**, and **input-driven execution.** First, a static analysis that respects the execution semantics of models is applied. It detects problematic elements that prevent the execution from progressing or reaching certain states. Second, to make the partial models executable, model-to-model (M2M) transformations [32] are used to refine the models automatically by adding decision points where the elements are missing. The refined models preserve the original behavior of the user-defined models and its execution does not get stuck and can reach all defined states in a finite number of execution steps, assuming proper inputs are provided. Third, during the execution, these decision points allow users to interactively (1) inspect and modify the system using debugging services, and (2) select one of the possible options to continue the execution. The interactive execution requires manual intervention, which can be repetitive, tedious, and time-consuming. To mitigate this problem, our approach includes a scripting language that captures user input as execution rules that can be applied automatically during execution, without stopping the execution and interacting with users. Also, the approach allows user input to be saved to the script of the execution rules or the design model, to avoid any unnecessary duplication by minimizing the effort required for writing the script and completion of the design model.

We extended our previous work on model-level debugging [13], [33] in the context of UML-RT (i.e., a language for modeling of soft real-time systems) [34], and created an execution engine of partial UML-RT models (PMExec [35]) that embodies the proposed framework. To maximize the impact of our work, our implementation is publicly available, and only uses open source tools, including the Papyrus-RT MDE tool, for modelling and code generation, and the Epsilon [36] tools for model transformation. We evaluated PMExec based on several use-cases that show that the static analysis, refinement, and handling of user input were performed with reasonable quality, and the overhead of approach, which is caused by the increase of complexity of models by the refinement, is manageable.
The rest of this paper is organized as follows. In Section 2, we describe our formalization and a running example. Section 3 presents a conceptual framework for execution of partial models, and Section 4 discusses the application of the framework into UML-RT. We present our evaluation approach and results in Section 6 and discuss the limitations and issues of our solution in Section 5. We review related work in Section 7, and then conclude the paper with a discussion, summary, and directions for future research.

2 Preliminaries

In this section, we define, exemplify, and discuss the formalization that we will use to specify and justify our refinement approach. To be able to illustrate our approach, we use the UML profile for Real-time systems (UML-RT). UML-RT [34], [37] is a language specifically designed for Real-Time Embedded (RTE) systems, with soft real-time constraints. Over the past two decades, it has been used successfully in industry to develop several large-scale industrial projects (e.g., [20]), and has a long, successful track record of application and tool support, via, e.g., IBM RSA-RTE [9], RTist [38], Eclipse eTrice [39], and Papyrus-RTE [40]. Our formalization is simplified, and focused on aspects that matter most to the execution of partial models. Interested readers can refer to [34], [37] for more in-depth information regarding UML-RT.

2.1 A Running Example

We use the control system of a simple traffic light (TrafficLight) as a running example throughout the paper. The structure of the system is shown in Figure 1, which consists of three components: UserConsole (UC), Controller (CTR), and StopLightDriver (SLD). The UC component collects user input, which it passes on to the CTR component, the component controlling the light. Using the corresponding messages, the CTR component sends the control actions to the SLD component, which transfers the messages through a hardware port to the traffic light.

Let us assume that we have a partial model of TrafficLight in which the behaviour of the component UC is missing, the behaviour of capsule SLD is complete, and the behaviour of capsule CTR is incomplete as shown in Figure 2 (e.g., no outgoing transition is defined from yellow). Let us discuss two exemplary situations where the execution of partial models can be helpful for early evaluation of design decisions and unit testing.

2.2 Modelling of a Real-time Embedded (RTE) System Using UML-RT

Definition 1. (Read function (Projection)) Let tp be a tuple of attributes \( \langle a_1, \ldots, a_n \rangle \) where \( a_1 \ldots a_n \) refer to attributes names. We use \( tp.a_i \) to read the value of attribute \( a_i \). E.g., to read the value of attribute name of tuple person = \( \langle \text{name}, \text{family} \rangle \) we can use person.name.

Definition 2. (Interface) Let us define an interface as a set of pairs \( \langle m, d \rangle \), where \( m \in M_a \) (i.e., a universal set of messages) is a message, and \( d \in \{\text{input, output}\} \) specifies whether a message is consumed (i.e., it is an input message) or produced (i.e., it is an output message). A message can have a payload, which is a set of values conveyed by the message.
Definition 3. (Component) Let us define a component as a tuple \( \langle P, V, \beta \rangle \), where \( P \subseteq P_u \) (i.e., a universal set of ports) is a set of ports, \( V \) is a set of variables, and \( \beta \) refers to the specification of the component’s behavior. A port is defined as a pair \( (t, conjugated) \), where \( t \) denotes the type of the port where the type of a port is an interface, and \( conjugated \in \{ true, false \} \) specifies whether or not the port is conjugated. The direction of messages of conjugated ports is reversed. We will use conjugation to ensure that connected ports are compatible by requiring that (1) they have the same type, and (2) one of them is conjugated while the other one is not. Non conjugated ports are also called base ports.

Definition 4. (Structure of an RTE system) Let us define the structure of an RTE system as a tuple \( \langle C, I, con, in \rangle \), where \( C \) is a set of components, \( I \) is a set of interfaces, \( con \) is a connectivity relationship \( \subseteq P_u \times P_u \), and \( in \) is an acyclic containment relation \( \subseteq C \times C \). Whenever two ports \( p_1, p_2 \) are connected by \( con \) (i.e., \( (p_1, p_2) \in con \)) then both have the same type (i.e., \( p_1.t = p_2.t \)) and exactly one of them must be conjugated. This condition ensures that connected ports are ‘compatible’.

Often, MDE tools provide timing services that can be used to define timed behaviors. To support time in our formalization, we assume that an RTE system contains a timing interface \( \langle startTimer, input, timeout, output \rangle \) and a component called RTS with a port of type timing. Any component using timing services requires a connection with the RTS component.

Let us exemplify the above definition in the context of the running example (see Fig. 1). The CTR is connected to UC and SLD using two ports UCPort (base port) and SLDPort (conjugate port), which are typed by interfaces ControlP and StopLightP, respectively. ControlP has two messages (on() and off()) and StopLightP has five messages (red(), green(), yellow(), on(), and off()).

Definition 5. (Action language) Action languages support primitive operations such as accessing/updating variables, arithmetic/logical expressions, control flow constructs, and sending messages. MDE tools provide action languages either by adapting a subset of well-known programming languages or by offering a specific, dedicated action language. E.g., Papyrus-RT uses a subset of C++ as the action language, UML assumes the use of the UML Alf action language [41], and YAKINDU [11] provides its own action language. In this work, we assume the existence of an action language with the standard capabilities, but do not define a particular syntax for it.

Definition 6. (Hierarchical State Machine (HSM)) We specify the behavior of a component \( c \) using a hierarchical state machine (HSM) that is defined as a tuple \( \langle S, T, in \rangle \), \( S = S_0 \cup S_c \cup S_p \) is a set of states, \( T \) is a set of transitions, and \( in \subseteq S_c \times (S \cup T) \) denotes an acyclic containment relation. States can be basic \( S_0 \), composite \( S_c \), or pseudo-states \( S_p \). Basic states are primitive states that the execution stays in until an outgoing transition is triggered. Composite states encapsulate a sub-state machine. Pseudo-states are transient control-flow states. There are six kinds of pseudo-states, called initial, choice-point, history, junction-point,
entry-point, and exit-point, (i.e., \(S_p = S_{in} \cup S_{ch} \cup S_{t} \cup S_{en} \cup S_{ex}\)). Composite and basic states can have entry and exit actions that are coded using an action language.

**Definition 7. (Transition)** Let \(inp(c)\) refer to the messages that can be received by component \(c\). A transition \(t\) is a 5-tuple \((src, guard, trig, act, des)\), where \(src, des \in S\) refer to non-empty source and destination of the transition respectively, \(guard\) is a logical expression coded using the action language, \(trig \subseteq inp(c)\) is a set of messages that trigger the transition, and \(act\) is the transition’s action coded using the action language.

Figure 2 shows an example of \(HSM\), and the corresponding graphical notations.

**Definition 8. (Helper functions)** Table 1 lists the helper functions (along with samples in the context of the running example, if possible) that will be used in the rest of the paper. Note that we treat the root of an \(HSM\) as a composite state, which can be accessed using the \(root(HSM)\) function.

**Definition 9. (Well-formedness constraints of \(HSMs\))** Following [9], [37], [40], we define the well-formedness constraints of \(HSMs\) as follows:
- Only transitions that start from a choice-point can have a guard, and no transition that starts from a pseudo-state can have a trigger. This constraint is defined to simplify the formalization, and our implementation addresses this case.
- There are no AND-states (orthogonal regions), and UML concepts fork, join, shallow history, and final states are also not used.
- Transitions cannot cross state boundaries, i.e., \(\forall t \in T : parent(t.src) = parent(t.des)\). Entry-point and exit-point states can be used to create transitions with different parents.
- States do not have idle (\(do\)) actions.
- There is no notation for history. Instead, any transition to a composite state is assumed to end in an implicit history state inside the composite state.
- Triggers of transitions starting from the same basic or composite state must be disjoint, i.e., \(\forall t_1, t_2 \in T : t_1.src = t_2.src \land t_1.src \notin S_p \Rightarrow t_1.trig \cap t_2.trig = \emptyset\).
- None of the pseudo-states except choice-points can have more than one on-going transition.
- Composite states and the root of the \(HSM\) cannot have more than one initial state.

Note that except the first constraint, these constraints are also enforced by existing UML-RT tools and none of them has been defined specifically for this study. Still, our approach can be extended to support AND-states and other concepts not offered in UML-RT.

**Definition 10. (Configuration)** A configuration \(\gamma\) of component \(c\) is defined as a tuple \((\sigma, \mathcal{E}, \mathcal{H})\) where \(\sigma \in S\) refers to the current state of the configuration, \(\mathcal{E}\) refers to a mapping from the component variables to values, and \(\mathcal{H}\) is a partial mapping from composite states to their last visited substates.

**Definition 11. (Execution of \(HSMs\))** We use Labeled Transition Systems (LTS) to define the execution semantics of an \(HSM\) of a component \(c\). An LTS is a tuple \((\Gamma, \mathcal{A}, \gamma_0, Q, \rightarrow)\), where \(\Gamma\) is a set of configurations, \(\mathcal{A}\) is the set of actions (i.e., entry, exit, and transition actions defined in \(HSM\)), \(Q\) is a first-in, first-out (FIFO) queue that stores received messages, \(\rightarrow\) is a transition relation (to avoid confusion with the syntax of \(HSM\)), we use the term ‘execution step’ instead of ‘transition’ in the rest of the paper), and \(\gamma_0 \in \Gamma\) is the initial configuration.

**Definition 12. (Execution Step)** An execution step is defined as a tuple \((\gamma, a_1 \ldots a_n, \gamma')\) that moves the execution from configuration \(\gamma = (\sigma, \mathcal{E}, \mathcal{H})\) (source configuration) to configuration \(\gamma' = (\sigma', \mathcal{E}', \mathcal{H}')\) (target configuration), while executing a possibly empty sequence of actions \(a_1 \ldots a_n\) with \(a_i \in \mathcal{A}\) for all \(1 \leq i \leq n\) that may result in updating \(\mathcal{H}\) and \(\mathcal{E}\), and producing outputs. We use the following notation to show an execution step.

\[ (\sigma, \mathcal{E}, \mathcal{H}) \xrightarrow{\text{exec}(a_1 \ldots a_n)} (\sigma', \mathcal{E}', \mathcal{H}') \]

**Definition 13. (Stuck Configuration)** A stuck configuration is a configuration that no execution step can start from, i.e., the execution cannot progress anymore when it reaches a stuck configuration. We use notation \(\gamma_s \rightarrow\) to show that configuration \(\gamma_s\) is a stuck configuration.

**Definition 14. (Initial Configuration)** The initial configuration of an \(HSM\) is is defined as \(\gamma_0 = (\text{initial}, \mathcal{E}_0, \emptyset)\), where \(\text{initial}\) refers to the initial state inside the root of the \(HSM\) (i.e., \(\text{initial} = S_{in} \cap \text{child}(\text{root}(\text{HSM}))\)) and \(\mathcal{E}_0\) refers to default values of the variables. The execution of the \(HSM\) starts from its initial configuration and if the initial state of the \(HSM\) is not defined, the execution cannot start (missing initial state).

**Definition 15. (Execution Rules of an \(HSM\))** Let us assume that \(\gamma = (\sigma, \mathcal{E}, \mathcal{H})\) refers to the current configuration. The rules in Figure 3 define the operational semantics [43] of \(HSMs\). The presentation of the rules makes use of definitions from Table 1. The rules are adapted from the execution semantics of UML-RT, presented in [37], [42].

**Rule-1, 2:** These rules are applicable to configurations whose current state is one of the pseudo-states, except for history and choice-point. According to Rule-1, an execution step is taken if there is an outgoing transition from the current state that executes the related actions and moves the execution to a new configuration. Conversely (Rule-2), if there is no outgoing transition, the execution stops there, and the current configuration is considered stuck (issue ‘broken chain’ in Sec. 4.1).

**Rule-3, 4, 5:** These rules are applicable to configurations whose current state is a basic state. If the current state is a deadlock state (Rule-3), the execution stops there, and the current configuration is considered stuck (issue deadlock state). Otherwise, if a message exists in the queue, one of the following rules is applied based on the result of the function \(\text{next}_I(\sigma, \text{head}(Q))\) (Ref. Table 1), a transition can be triggered, which results in an execution step that executes the related actions and moves the execution to a new configuration as shown in the bottom of the rule (Rule-4). Conversely (Rule-5), if a transition cannot be triggered (i.e., the incoming message is an unexpected message), an
transitions from the current state are evaluated, and the first transition whose guard evaluates to true is selected. This execution step cannot be taken. We consider the configuration to be stuck. However, it is also possible to configure the RTS to throw away the unexpected messages. As a result, the execution can recover and continue. We argue that in the domain of RTE systems, in which most of the applications are safety-critical, it is not safe to throw away any message.

Rule-6, 7: These rules are applicable to configurations whose current state is a composite state (implicit history state). If function next_s(σ, H) (Ref. Table 1) returns a state, then an execution step is taken that applies the entry code of the related composite state and moves the execution to a new configuration, as shown in the bottom of the rule (Rule-6). Conversely, if the selection is unsuccessful, the execution cannot move, and the configuration is a stuck configuration (Rule-7). This can happen due to two reasons: (1) the current state has no child (issue childless composite state), (2) the current state has no initial state (issue missing initial state).

Rule-8, 9: These rules are applicable to configurations whose current state is a choice-point. Guards of the outgoing transitions from the current state are evaluated, and the first transition whose guard evaluates to true is selected. This results in an execution step that executes the related action code and moves the execution to a new configuration, as shown in the bottom of the rule (Rule-8). Conversely, if none of the outgoing transitions’ guards holds (issue non-exhaustive guards), the execution cannot move, and the configuration is a stuck configuration.

Note that Rules 2, 3, 5, 7, and 9 (all of which are related to stuck configurations) can be merged into one rule. However, we use the different rules for the sake of clarity.

Definition 16. (Execution of an RTE system) The execution of an RTE system can be defined as a collection of its components’ HSM executions, which interact with each other by passing messages. We do not describe the details of the composition here, and we assume that the RTE system execution is managed by a controller. The controller is responsible for scheduling and message-passing between components, and guarantees that an incoming message will be fully processed before the processing of the next message starts (run-to-completion semantics).

Figure 3: Execution rules of an HSM adapted from [37], [42]

3 A CONCEPTUAL FRAMEWORK

Figure 4 shows a conceptual framework for executing partial models, which consists of three parts (Static Analysis, Automatic Refinement and Input-driven Execution). In the following, we discuss the setting and the three parts.

3.1 Setting

As discussed in Section 1, a partial model can be executed for different purposes. In all cases, the completeness level of a model is often decided by different stakeholders, based on different constraints and goals. We do not have an automatic check to determine when a model is complete. Instead, we allow users to specify the completeness level of each component based on their need. Supported levels are clevels = {complete, partial, absent/ignored}.

Complete components are assumed to be complete, and are not required to be analyzed and refined. By default, each component is assumed to be complete, unless its completeness level is explicitly set to something else.

Partial components are assumed to be incomplete. Thus, their current specification (structure and behavior) is analyzed and refined.

Absent/ignored components are assumed to have no behavior specification. However, their existence may be necessary for the execution of other (partial and complete) components, due to the dependency between them. Thus, the absent/ignored components are analyzed based on their structure (inputs and outputs) and possible dependencies of other components on them. Then they are given behaviour sufficient for simulation.

The setting allows the execution of the models for different purposes. E.g., in the context of the running example which is discussed in Subsection 2.1, we can set the completeness level of CTR to partial, that of SLD to complete, and that of UC to absent/ignored to execute the system for Scenario-1 (evaluation of design decision). For scenario-2 (unit testing), the level of CTR should be set to partial and the levels of the other components to absent/ignored.
3.2 Static Analysis

Assuming that the execution semantics of the language is defined, we perform static analysis with respect to the execution semantics to detect the problematic elements that can cause a problem for the execution. Depending on the semantics of the language different types of problems may be detected. In the context of state machines, the problems associated with executing partial models fall into two groups: *lack of progress* and *lack of reachability*. The former is related to situations in which the execution cannot progress anymore from a certain point. The latter concerns the execution being unable to reach certain, specific states. The static analysis is performed on the user-defined model and identifies problematic elements including: (1) missing elements, (2) existing elements with problematic specifications, and (3) missing and unhandled inputs.

3.3 Automatic Refinement

During the refinement phase, depending on the results of the static analysis and the setting, the user-defined model is refined automatically using model-to-model transformation techniques. The goal of the refinement is to fix the problematic elements or modify them in such a way that users can provide more information about them during execution. Depending on the modelling language, certain language constructs can be used to enable models to interact with users during the execution. E.g., for HSMs, we use choice-points with certain actions and guards.

The refinement should meet the following constraints: (1) Refined models must preserve the original behavior of the user-defined models. (2) The execution of the refined model must not get stuck, assuming proper inputs are provided. (3) The execution of the refined model must be able to reach all defined states in a finite number of execution steps, assuming proper inputs are provided. (4) The execution of the refined model must allow users to select one of the possible options to fix the problematic element. The options must be exhaustive and include all possible situations which can be applied at design time without limiting the users to only a subset of them.

3.4 Input-driven Execution

The refined model can be executed via interpretation or code generation. During execution, the executed model provides an interface for reading user input either in interactive or batch mode. It is also crucial to provide debugging facilities. Thus, users can investigate the execution before providing inputs.

4 Application of the Framework to Partial UML-RT Models

Generally, the discussed framework to allow execution of partial models can be applied in the context of different modeling languages. However, since the execution of models is a language-dependent concept, there is no way to provide a generic implementation of the framework using existing techniques and tools. In the rest of this section, we discuss the application of the framework for executing partial UML-RT models and demonstrate a tool that embodies the framework.

4.1 Static Analysis

In the following, we discuss the details of the static analysis of UML-RT models, with respect to the execution semantics of UML-RT as discussed in Def. 11. We categorize the problems based their effect on lack of progress or reachability. Note that a lack of progress entails a lack of reachability.

4.1.1 Lack of progress

Based on the execution rules of HSMs (see Def. 15), the execution of an HSM can be stopped due to several issues, which can be divided into two groups, as follows.

**Missing/problematic elements:** The execution of an HSM cannot start, or moves to a stuck configuration, due to the following issues.

- **P1:** missing initial state (see Def. 14),
- **P2:** childless composite states (see Rule-7 of Fig. 3),
- **P3:** broken chain (see Rule-2 of Fig. 3),
- **P4:** deadlock state (see Rule-3 of Fig. 3),
- **P5:** unexpected messages (see Rule-5 of Fig. 3),
- **P6:** non-exhaustive guards of choice-points (see Rule-9 of Fig. 3).
4.1.2 Lack of Reachability

Anything causing the lack of progress problem also causes a lack of reachability. There is no way for the execution to reach any state after being stopped. In addition, the following missing or problematic elements can cause a lack of reachability.

- **P9**: isolated states are states that do not have incoming transitions (with the exception of initial and history states). There is no way for the execution to reach these states.
- **P10**: not-takeable transitions originate from a basic or composite state and have no trigger.
- **P11**: as discussed, one of the main benefits of the execution of partial models is enabling early evaluation of different design decisions, the support of which requires all states to be reachable during the execution in a finite number of steps. Otherwise, some design decisions cannot be evaluated due to the lack of reachability issue. For example, in the context of the running example (see Fig. 2), assume that transition t22 is missing, and a user needs to evaluate the effect of action of t23. The evaluation is not possible without steering the execution to state s22. Thus, we define another condition that concerns steering the execution from configurations whose current state is a basic state to any configuration whose current state is any basic state.

Except for P11, the elements with these issues can be queried from the structure of a component c with an HSM as follows.

\[ P9 \leftarrow \{ s \in S \setminus (S_{in} \cup S_{gh}) : \text{in}_\text{trans}(s) = \emptyset \} \]
\[ P10 \leftarrow \{ t \in T : \text{src}(t) \in S_b \cup S_c \land \text{trig}(t) = \emptyset \} \]

As for P11, this capability needs to be addressed in all basic states, i.e., \( P11 \leftarrow S_b \). Note that sets \( P1 - P11 \) are not disjoint and an element may have several issues. For instance, in the context of the running example (see Fig. 2), s23 is a deadlock state and has a reachability problem, i.e., s23 \( \in P4 \cap P11 \).

4.2 Refinement of Partial UML-RT Models

In the following, we discuss the details of the refinement, applied to fix the problematic elements (P1-P11) extracted during the analysis phases.

**Main Loop of the Refinement.** Algorithm 1 shows the main loop of the refinement of a UML-RT model. It takes a UML-RT model and a setting as inputs. A setting is a set of tuples \( \langle c \in C, clevel \in clevels, c \rangle \), where \( c \) is a component and \( clevel \) specifies the level of completeness of components, and let \( O \) be a set of possible output messages of absent/ignored components, then \( P7 \leftarrow I \cap O \).

Detecting \( P8 \) at design time suffers from a similar problem as P6. Thus, we overestimate again and assume that all partial components have this problem, i.e., \( P8 \leftarrow \) all partial components). As we will discuss later, we provide debugging commands for sending messages to the other components from partial components, during the execution. That way, users can fix this problem by manually injecting the related messages during the execution.

```
Algorithm 1: Refinement of a Partial UML-RT Model

Input: A UML-RT model sys and a setting conf
Output: A refined model

1. Add a debugging interface dbg_int and a debugging agent dbg_agent into sys
2. Add ports types with timing and dbg_int into
dbg_agent for all \( c \in \text{sys}.C \) // sys.C (components of sys)

3. switch c.conf do
   case partial do
     Add port p of type dbg_int into component c
     Add a connection using port p with dbg_agent
     \[ c.\beta \leftarrow \text{refineHSM}(c.\beta, c) \]
   case absent/ignored do
     Add port p of type dbg_int into component c
     Add a connection using port p with dbg_agent
     Delete all elements from HSM of c (c.\beta)
     \[ c.\beta \leftarrow \text{refineHSM}(c.\beta, c) \]
   otherwise do
     // No refinement

4. \( \text{dbg}_\beta \leftarrow \text{refineHSM}(\text{dbg}_\beta, c) \)
```

Except for P6, the elements with these issues can be described by queries on the structure of the HSM, as follows.

\[ P1 \leftarrow \{ s_c \in (\text{root}(\text{HSM}) \cup S_h) : \text{Sint} \cap \text{child}(s_c) = \emptyset \} \]
\[ P2 \leftarrow \{ s_c \in (\text{root}(\text{HSM}) \cup S_h) : \text{child}(s_c) = \emptyset \} \]
\[ P3 \leftarrow \{ s \in S_h \setminus (S_h \cup S_{ch}) : \text{out}_f(s) = \emptyset \} \]
\[ P4 \leftarrow \{ s \in S_h : \text{handled}(s) = \emptyset \} \]
\[ P5 \leftarrow \{ s \in S_h : \text{inp}(c) \setminus \text{handled}(s) \neq \emptyset \} \]

As for P6, we assume that all choice-points have this problem, i.e., \( P6 \leftarrow \{ s \in S_{ch} \} \). This is an overestimation, and covers all possible situations of P6. Checking the exhaustiveness of guards of a choice-point during design time is a difficult problem, and requires expensive computation. Thus, fixing this problem at design-time can increase the exhaustiveness of guards of a choice-point during design time significantly, and even make it unsolvable. Also, the applicability of the existing techniques on partial models is not supported by default, and requires extra work and research.

**Missing inputs:** A prerequisite for taking an execution step from basic states is the reception of a new message (see Rule-4 of Fig. 3) that can enable an outgoing transition from the current state. The execution can be stuck, if the required messages for triggering possible transitions are not produced by the connected components. This can happen for two reasons: (1) the connected component lacks a behavior specification, i.e., components are set as absent/ignored (P7), (2) the behavior of a connected component is partial (P8). Detecting P7 is trivial and can be determined from the interface specification of components. Let \( I \) be a set of possible input messages of all partial and complete components, and let \( O \) be a set of possible output messages of absent/ignored components, then \( P7 \leftarrow I \cap O \).
Algorithm 2: Refinement of HSM (refineHSM)

| Input | An HSM \( sm \) and a component \( c \) |
|-------|-------------------------------------|
| Output| A refined HSM |

// The following loop refines states in order of their nesting level, with the least deeply nested state (root(HSM)) refined first.

1. for all \( s_c \in root(sm) \cup (sm.S \in S_c) \) do
2.     \( dec_p \leftarrow add_state(s_c, S_{ch}) \) // Add decision point
3.     if \( s_c \in P2 \) then // Fix childless composite state (P2)
4.         \( state_p_h \leftarrow add_state(s_c, S_h) \)
5.     if \( s_c \in P1 \) then // Fix missing initial state (P2)
6.         \( add_state(s_c, S_{in}) \)
7.     forall \( sp \in (child(s_c) \cap P3) \setminus dec_p \) do
8.         \( add_trans(sp, dec_p) \) // Fix broken chain (P3)
9.     forall \( s_{ch} \in child(s_c) \setminus dec_p \) do // Fix non-exhaustive guards for choice-points (P6)
10.    \( t_1 \leftarrow add_trans(s_{ch}, dec_p) \)
11.    \( t_1.gard \leftarrow \neg \forall (guard(out\_trans(s_{ch}))) \)
12.     forall \( sb \in child(s_c) \cap P11 \) do // Fix unexpected messages (P5), deadlock states (P4), and step 1 of fix for P11
13.        if \( sb \in (P4 \cup P5) \) then
14.            \( t_2 \leftarrow add_trans(sb, dec_p) \)
15.            \( t_2.trig \leftarrow imp(c) \setminus handled(sb) \)
16.     forall \( s \in (child(s_c) \setminus (S_{in} \cup dec_p)) \) do // Fix isolated states (P9) and step 2 of fix for P11
17.        \( t_3 \leftarrow add_trans(dec_P, s) \)
18.     forall \( t \in P10 \) do // Fix not-takeable transition (P10)
19.         \( t.src = dec_p \)
20.     forall \( s_{cc} \in child(s_c) \cap S_c \) do // Step 3 of fix for P11
21.         \( ex_p \leftarrow ex_p \cup add_state(s_{cc}, S_{ex}) \)
22.         \( en_p \leftarrow en_p \cup add_state(s_{cc}, S_{en}) \)
23.         \( to\_child \leftarrow add_trans(dec_p, en_p \cap child(s_{cc})) \)
24.         \( from\_child \leftarrow add_trans(ex_p \cap child(s_{cc}), dec_p) \)
25. if parent(s) ≠ ∅ then // Last step of fix for P11
26.         \( to\_parent \leftarrow add_trans(dec_p, ex_p \cap child(s_{cc})) \)
27.         \( from\_parent \leftarrow add_trans(en_p \cap child(s_{cc}), dec_p) \)

the component. The algorithm first adds a new component to the model, called \( \text{dbg}_\text{agent} \) with an empty HSM, creates a debugging interface, and adds debugging and timing ports into \( \text{dbg}_\text{agent} \). \( \text{dbg}_\text{agent} \) is responsible for receiving from external applications and transferring \( \text{dbg} \) messages to partial and absent/ignored components. After setting up \( \text{dbg}_\text{agent} \), the algorithm tries to apply certain refinements based on the setting of the components, as follows.

1) For partial components, it adds a debugging port into the components and creates a connection between them and \( \text{dbg}_\text{agent} \). This allows them to receive the \( \text{dbg} \) message during the execution, which is essential for fixing elements in P7-P8. Then it calls the refineHSM function, which applies the behavioral refinement to fix the issues (line# 4-7).

2) The behavior of absent/ignored components are removed, which results in an empty HSM. Then, their empty HSM is refined, which results in an HSM that can receive and send all possible input and output messages of the component (line# 8-12).

3) Finally, the HSM of \( \text{dbg}_\text{agent} \) is also refined as a absent/ignored component that results in an HSM capable of processing debugging commands (line# 14).

Behavioral Refinement. Algorithm 2 presents function refineHSM, which refines the HSM of a component with respect to elements in P1-P11 except for elements in P7-P8. Before discussing the details, let us define \( add\_state(s_c \in S_c, ty \in S) \rightarrow S \) as a function that adds a state of type \( ty \) inside the \( s_c \) and \( add\_trans(src, trg \in S) \rightarrow T \) as a function that adds a transition from state \( src \) to state \( trg \).

The algorithm iterates over all composite states, and the root of the HSM, and refines them in 9 steps, as follows.

1) It creates a choice-point state called \( dec_p \). \( dec_p \) is used as a decision point during the execution (line# 2). When a specification is missing, we refine the HSM so that the execution is directed to \( dec_p \).

2) Fix elements in P2 which have no child, by adding a new basic state inside the related state (line# 3-4). Note that the added basic state has issues P4, P5, and P9, and requires the corresponding fixes.

3) Fix elements in P1 which miss initial states, by adding a new initial state inside the related state (line# 5-6). Note that the added initial state has issue P3, and requires the corresponding fixes.

4) The elements in P3 (Broken chain) are fixed by adding a transition from the problematic states to \( dec_p \) (line# 7-8).
Figure 5: Refined version of CTRSM in Fig. 2 (added elements are coloured blue, and modified elements are coloured red)

This ensures that the execution will move to dec_p instead of stopping at the problematic states, and thus users can steer the execution to other states from dec_p.

5) Fix elements in P6 (Non-exhaustive guards) by adding a transition from each choice-point to dec_p so that its guard is set to the negation of the disjunction of the outgoing transitions’ guards (line# 9-11). This ensures that the execution moves to the dec_p if none of the guards of the outgoing transition holds, instead of stopping there. Arguably, this solution is much cheaper than the design time analysis to detect and fix this issue.

6) During this step, a new transition is added from each basic state to dec_p and its trigger is set to all un-handled messages in the state (line# 13-15). This not only fixes the elements in P4 (deadlock state) by adding a transition from them to dec_p, but also (1) allows all un-handled messages to be handled as the new transition’s trigger (P5), and (2) allows the steering of the execution from any basic state to dec_p which is the first step of the fix for elements in P11.

7) A transition is added from dec_p to all basic states and isolated states (line#16-17). This fixes issue P9 (isolated states), and also allows the steering of the execution to any basic state from dec_p which is the second part of the fix for P11.

8) To fix not-takeable transitions (P9), their source is changed to dec_p (line# 18-19). This allows them to be taken whenever the execution reaches dec_p. Since each state has a transition to dec_p which is added in step 6 with a trigger set to all un-handled messages, the not-takeable transitions can be activated by any of the un-handled messages. Note that the dbg message, which is added using Algorithm 1 is assumed to be an un-handled message.

9) At the end, an exit-point (line# 21) and an entry-point (line# 22) states are added to each composite state to allow the execution to be steered from their sub-states to states in their parent state and vice-versa, which is the last part of the fix for elements in P10. Two transitions to_parent and from_parent allow the execution to be steered from their sub-states to states in their parent state, and transitions to_substates and from_upper allow the execution to be steered from states in their parent state to their sub-states (line# 20-27).

Note that the refinement algorithms do not contain details for the actions which are added to HSMs. E.g., (1) added actions to the HSM of dbg_agent for processing and injecting the message dbg, (2) guards of outgoing transitions from decision points which are set in a way that allows users to select one of them, (3) actions of incoming transitions to decision points that call a function to read user input. Interested readers can refer to the source code of the refinement [44].

4.2.1 Refinement Result on the Running Example

Figure 5 shows the result of running Algorithm Example on the partial CTRSM with partial completeness level in which transitions and states are annotated with corresponding issues P1-P11. Let us review some examples of how the execution can be performed despite missing specifications:

1) No transition from yellow to red was possible in the original model. This is fixed by adding transitions from yellow and red to dec_p and vice-versa. Thus, any of the input messages or dbg messages can move the execution to state dec_p from state yellow where users can select one
of the outgoing transitions (e.g., the transition from \( \text{dec}_p \) to state \( \text{red} \)). (2) The transition \( t_{13} \) is not-takeable in the original model and its action cannot be executed. In the refined model an \( \text{off} \) or \( \text{dbg} \) message can move the execution to \( \text{dec}_p \) in which the transition \( t_{13} \) is one of the possible transitions and can be selected and its action be executed.

### 4.3 Execution of Refined Partial UML-RT Models

In this section, we discuss our method for the execution of incomplete UML-RT models. The discussion will emphasize key concepts over low-level implementation detail. The definitions below identify two such concepts.

**Definition 17.** (Execution Context) Intuitively, an execution context captures the most relevant runtime information of an execution stopped at some decision point. Formally, an execution context is a tuple \( \langle \gamma, \text{dec}_p, m, \mathcal{O} \rangle \), where \( \text{dec}_p \) refers to the decision point at which the execution is stopped, \( \gamma \) denotes the configuration (see Def. 10) right before the execution reached \( \text{dec}_p \), \( m \) denotes the last processed message by the HSM (the trigger of the most recently taken transition starting from \( \gamma, \sigma \)), and \( \mathcal{O} \) is a list of possible options available to continue the execution (i.e., the transitions originating from \( \text{dec}_p \)).

**Definition 18.** (Execution Rule) We define an execution rule as a tuple \( \langle h, b \rangle \), where \( h \) refers to the header and \( b \) refers to the body of the rule. A header is a tuple \( \langle \text{name}, \text{where}, \text{when} \rangle \), where \( \text{name} \) refers to the name of the execution rule, \( \text{where} \) refers either to the qualified name of a state (\( \text{component.state} \)), name of a component, \( * \), or \( \text{*\.state} \) as shown in Listing 1 (Line #7), and \( \text{when} \) refers to a boolean condition. A body is a sequence of statements as defined in Listing 1. The semantics and use of execution rules is discussed in Section 4.3.3.

#### 4.3.1 Execution Flow of a Refined Partial Models

As discussed, the partial models are refined by adding decision points where elements are missing or are partial that allow users to execute the partial models and provide information about the missing or partial element during the execution. This requires a mechanism that (1) enables executed models to obtain user input either in interactive or batch mode, (2) provides debugging features to investigate and modify the execution of the model.

Figure 6 shows the execution flow of a refined HSM in which a debugging probe is hooked into the execution of an HSM by adding relevant actions in the initial transition of the HSM. When an HSM starts executing, two threads \( \text{main} \) and \( \text{probe} \) are started but only one of them is active at each time of the execution. Thread \( \text{main} \) executes the models as specified until it reaches a decision point where it sends the relevant execution context to the \( \text{probe} \) and waits for the user input. Thread \( \text{probe} \) starts a debugging session (batch or interactive) that allows users to investigate the execution and provide input. At the end of the session, the user input is returned to thread \( \text{main} \) to continue the execution. The interaction between the threads is simply a function call from thread \( \text{main} \) to the \( \text{probe} \) that is implemented using an action in the transitions ending at the decision points. In the following subsections, we review two execution modes of partial models.

#### 4.3.2 Interactive Execution

With the interactive execution, users are allowed to issue debugging commands listed in \textit{interactiveStatement} of Listing 1, e.g., view and modify variables. Most of debugging services are ported from MDebugger [33]. The new debugging commands to facilitate the execution of incomplete models are as follows:

1) \textit{viewCmd} lists the possible options to continue the execution.

2) \textit{selectCmd} allows users to select one of the possible options. Note that \textit{selectCmd} is the last statement that is applied when the execution has been stopped, and any command after that in the body of the rule is ignored (similar to the \textit{return} statement in many programming languages). Also, \textit{selectCmd} can accept more than one option during the batch execution, and in that case the execution switches to interactive mode to capture the user input.

3) \textit{simpleStatement} allows users to define new variables which can be accessed during the debugging session.
and to access all attributes (i.e., HSM’s variables and newly defined variables during the debugging session) and modify them using arithmetic expressions.

4) saveCmd allows users to save their decision during the interactive session. We discuss this command in detail in Section 4.3.3.

5) umlrtCmd consists of send, reply, and receipt commands. Commands send and reply allow users to send/reply (inject) messages to other components. Command receipt accepts a message as an input and returns true if the message is the most recently received message by the component, and false otherwise.

4.3.3 Batch execution

Interactive execution stops and delays the execution which is not suitable in some situations, especially for the debugging of time-sensitive systems, to repeat a debugging scenario, or to test and explore a design decision. For these situations, a batch execution mode is supported that allows users to provide inputs using a script that consists of execution rules (see Def. 18). An execution rule prescribes how the execution of a refined partial model is to be continued when the current execution context matches the when of the rule and the when of the rule evaluates to true.

Depending on the current execution context and defined rules, multiple rules may be applicable at each time, but only one rule can be applied at each time. The rule selection for a decision point of an execution context with component c and the current execution state s is performed by following the steps below:

1) Guards of rules whose when (i.e., component and state name) is equal to c and s are evaluated based on the order of their appearance in the script file of the rule. The first rule whose guard holds is selected and applied.

2) If (1) is unsuccessful, guards of rules whose state name is exactly equal to s and component name is equal to ∗ or empty are evaluated based on the order of their appearance in the rules’ script file. The first rule whose guard holds is selected and applied.

3) If (2) is unsuccessful, guards of rules whose component name is exactly equal to c and state name is equal to ∗ or empty are evaluated based on the order of their appearance in the rules’ script file. The first rule whose guard holds is selected and applied.

4) If (3) is unsuccessful, guards of rules whose state and component name is ∗ are evaluated based on the order of their appearance in the script file of the rule. The first rule whose guard holds is selected and applied.

5) If none of the above holds, the execution stops and the user is asked to provide input to continue the execution.

4.4 Automation

In general, the partial models that we consider exhibit one of two kinds of partialness: un-intentional and intentional. The former is related to situations (e.g., early debugging) in which the model is still under development, and not yet complete, due to the iterative and incremental nature of the software development process. The latter relates to situations (e.g., unit testing and partial analysis) in which users intentionally execute a complete model as a partial model often by writing scripts for execution rules to mock the ignored or unavailable part of the model. This can, e.g., increase the efficiency of testing or help deal with the unavailability of external components that the model relies on.

With un-intentional partialness, the user has to provide input (in the form of interactive decisions at runtime or execution rules) to steer the execution of the refined partial model. It is possible that this input resolves the partialness in a generally satisfactory way and that the user then also wants to use it for the next incremental development step and apply it to the design model. However, as we discuss later, our approach is careful to avoid duplicate effort from the user by allowing the input to be used directly to update the design model, instead of requiring the user to provide it again when completing the design model. While this double effort may incur negligible costs for the debugging of only a small part of a partial model, its cost can be significant for the debugging of a large part of a partial model, due to the large number of inputs that may need to be provided. Note that in the case of intentional partialness, the model is already complete, and writing the scripts for execution rules is only for simulation and mocking of the existing components.

To minimize the overhead of writing execution rules, and to reduce the need for double efforts, we provide three automation features, including (1) generation of default execution rules, (2) saving of users’ interactive decisions as execution rules, and (3) application of execution rules into the design model. As shown in Figure 7, the features are complementary and allow users to automatically create execution scripts and update the design model by application of the execution rules. In the following, we discuss the details of each feature.

4.4.1 Generation of Default Execution Rules

As discussed, at each decision point that has been added during the refinement (see Section 4.4), users are given a set of all possible options, one of which needs to be selected to continue the execution of the model. Considering and selecting one of the options can be time-consuming, specifically for the execution of large partial models. To minimize the efforts for making decisions, we generate default execution rules for the decision points that filter out options that are less likely to be selected by users. When the filtering results in a single option, the generated rule executes the model without user intervention, otherwise one of the remaining options needs to be selected by the user either interactively or by editing the generated rule. Note that the default execution rules are generated as a script and can be viewed, modified, or even ignored by users depending on the execution scenarios.

Algorithm 3 presents the method for the generation of default execution rules. The algorithm accepts as input the refined model and the partial elements which have been detected by the static analysis (P1-P11 as discussed in Section 4.1) and then it generates a set of execution rules.

For each decision point dec_p, the algorithm iterates over all transitions that end at dec_p (line# 4-5) and creates at least one rule for each transition (line# 4-12). The when part
of each rule is set to the state the transition originated from, and the when part is set to a guard indicating the arrival of a message \( m \) triggering the transition (if any). Note that no rule is created for message \( dbg \) (i.e., the debugging message). Thus, when the default rules are used, the execution can still be steered to any specific state by injecting the debugging message. Finally, the algorithm calls the function \( genRuleBody \) (line# 13), which generates a body for the rule.

Let us assume that when applied to a transition \( t' \) that may have been refined by Algorithm 2, the function \( org(t') \) returns the original transition \( t \) before the refinement. Function \( genRuleBody \) applies the following three heuristics to filter out options less likely to be of interest to the user and generates the body of the rule.

1) If the rule handles a choice-point (i.e., the when part of the rule is a choice-point such as \( ch_1 \)) with non-exhaustive guards, then the algorithm omits the transitions into states that are reachable via the transitions leaving \( ch_1 \) (line# 20-23) in the original model. The rationale is that the user has already decided when those states are to be reached from \( ch_1 \) by specifying the guards of the outgoing transitions from \( ch_1 \) in the original model.

2) If the rule handles an unexpected message (i.e., the guard in the when part of the rule indicates the arrival of an unexpected message) (line# 24-29), the algorithm performs one of the following actions. (a) It selects not-takeable transitions that end at an isolated state, if any (line #25); (b) otherwise, it selects not-takeable transitions, if any (line #26-27); (c) otherwise, it selects transitions that end at an isolated state (line #28-29); and (d) otherwise, it selects all possible transitions (line #33-34).

Note that selecting a transition for an unexpected message has the same effect as adding the unexpected message as the trigger to the transition. The rationale for this heuristic is that the trigger of not-takeable transitions is missing, and setting the trigger for them is likely more helpful to make the model executable than the appending of a new message to the trigger of transitions that are already defined in the original model. Similarly, since an isolated state does not have any incoming transition, there is more of a need to fix it compared to states that already have incoming transitions.

3) If the rule handles a broken chain, the algorithm tries items c) and d), in the same way as the previous heuristic (line# 30-31).

We note that the generated rules may require further manual modification, due to the fact that a rule contains more than one option for selection, or the user finds one of the heuristics unsuitable for their needs. However, the generated rules should provide a useful initial version even in these cases.

For illustration, Listing 2 shows the default execution rules that are generated for the refined CTRSM (see Fig. 5).

```plaintext
1  rule r1 where state off when receipt(timeout) {  
2       select state off using t13  
3  }  
4  rule r2 where state off when receipt(off) {  
5       select state off using t13  
6  }  
7  rule r3 where state yellow receipt(timeout) {  
8       select state red|green|yellow|off  
9  }  
10  rule r4 where state yellow receipt(off) {  
11       select state red|green|yellow|off  
12  }  
13  rule r5 where state red receipt(off) {  
14       select state red|green|yellow|off  
15  }  
16  rule r6 where state green receipt(off) {  
17       select state red|green|yellow|off  
18  }
```

Listing 2: Default execution rules that are generated for the refined CTRSM (see Fig. 5)
### Algorithm 3: Generation of execution rules with a default body

**Input**: Refined HSM $sm'$, problematic elements (P1-P11)

**Output**: Set of execution rules

1. Let $R$ be an empty set
2. Let $D$ be a set that contains all of $dec_p$ of $sm'$ which have been added during refinement
3. Let $P_e$ be exit-point/entry-point states that are added during the refinement
4. **for all** $dec_p \in D$ do
   5. **for all** $t \in \{ t : t.des = dec_p \}$ do
      6. if $t.src \notin P_e$ then
         7. $M \leftarrow t.trig \setminus dbg$
         8. if $M = \emptyset$ then
            9. Add message dummy in $M$
         10. **for all** $m \in M$ do
             11. Create a new rule $r$
             12. $r.h.where \leftarrow t.src$
             13. if $m \neq dummy$ then
                 14. $r.h.when \leftarrow m$
                 15. $r.body \leftarrow genRuleBody(r, dec_p)$
                 16. Add $r$ into $R$
      17. return $R$

#### Function $genRuleBody$ (Rule $r$, Decision point $dec_p$)

18. $O \leftarrow \{ t : t.src = dec_p \}$
19. if $r.h.where \in P6$ then
   20. $T_{tmp} \leftarrow \{ t : org(t).src = r.where \}$
   21. $S_{tmp} \leftarrow \{ s : s = t.des \land t \in T_{tmp} \}$
   22. $O \leftarrow O \setminus \{ t : t.src = dec_p \land t.des \in S_{tmp} \}$
   23. else if $r.h.when \in P5$ then
      24. $O_{tmp} \leftarrow O \cap \{ t : org(t) \in P10 \land org(t).des \in P4 \}$
      25. if $O_{tmp} = \emptyset$ then
         26. $O_{tmp} \leftarrow O \cap \{ t : org(t) \in P10 \}$
      27. if $T_{tmp} = \emptyset$ then
         28. $O_{tmp} \leftarrow O \cap \{ t : org(t).src \in P4 \}$
      29. else if $r.h.where \in P3$ then
         30. $O_{tmp} \leftarrow O \cap \{ t : org(t).src \in P4 \}$
         31. $O \leftarrow O_{tmp}$
         32. if $O = \emptyset$ then
            33. $O \leftarrow \{ t : t/src = dec_p \}$
            34. Generate body of $r$ according to $O$

#### 4.4.2 Save user decisions (inputs) as execution rules

As discussed, via interactive execution, users need to provide input to steer the execution at decision points. Depending on the goals of the execution, users may need to repeat the execution, and therefore providing the same input can be time-consuming and tedious. To deal with this issue, a feature is provided that allows users to save interactive decisions in the form of execution rules. Thus, the execution can be repeated based on the saved rules without having to provide the input again. The implementation of the feature is heavily dependent on appropriate support for recording and viewing the execution of a partial model together with the user decision (input) provided during the execution. In the following, we discuss a high-level overview of how this feature is realized. A central notion is that of an execution record.

**Definition 19.** (Execution Records) Let us assume that the execution of a partial model is saved as a set of records $(c,d,o)$, where $c$ denotes the execution context at the time of the decision, $d$ refers to a sequence of debugging commands that have been issued by the user while the execution was stopped (i.e., from when the decision point was first reached and until the execution is resumed with a select command), and $o$ refers to the runtime decision (input) that is taken by the user (i.e., the argument of the select command).

Function $saveDecisionsAsRules$ in Algorithm 4 presents how the interactive decisions are saved as execution rules. It accepts a set of execution records and returns a set of execution rules. The function first checks that the decisions are consistent (i.e., unique decisions are taken for the same execution contexts) and then resolves inconsistencies by consulting with users, as will be discussed below. Then, it finds the rule that matches the execution context, and if no rule is matched, it creates an execution rule based on the execution context. Finally, it generates the body for the execution rule by using the issued debugging commands that modify the execution state (e.g., changing a variable value). Note that the interactive debugging commands (i.e., ‘dbgCommands’ and ‘umlrtCmd’ in Listing 1) are a subset of the statements used for writing the body of an execution rule and there is no mismatch that complicates the use of sequences of debugging commands as rule bodies.

**Resolving the inconsistency.** Users are allowed to view their previous decisions and save one or more decisions as rules. When a user wants to save more than one decision, it is possible that some of the decisions are not consistent with each other, such that different decisions are taken at the same decision point for the same execution context. Thus, saving these decisions can cause non-determinism and should be avoided. To resolve inconsistencies between decisions, we ask users to select one of them.

#### 4.4.3 Application of execution rules into design model

To mitigate the issue of double effort, we allow users to apply the execution rules into the design model automatically. To do that, we use the information in the execution rules about how to resolve partiality at runtime to fix the partiality in the design model. This feature is useful when users are satisfied that the way to deal with partiality at runtime expressed in the rules is correct and final, and they want to fix and remove partiality in the design model.

Application of execution rule into the design model is addressed by function $saveRuleToModel$ in Algorithm 4. It accepts the original state machine ($sm$) and an execution rule ($r$) as input and fixes the relevant partiality in $sm$ according to the definition of $r$, when there is only one possible solution to fix the partiality that is addressed by $r$ and $r.where$ explicitly refers to a state, i.e., $r.where$ does not contain * or does not refer to a component. The function first extracts the selected states and transitions based on the select statements from the rule’s body, e.g., the selected states of rule $r1$ and $r3$ in Listing 3 are $\{off\}$ and
Algorithm 4: Saving user decisions as execution rules and application of execution rules into design model

```plaintext
1 Function saveDecisionsAsRules (A sequence of execution record L)
2     Check and resolve the inconsistencies of the decisions in D
3     Let R be an empty set
4     forall l ∈ L do // l is an execution record (ref. Def. 19)
5         r ← \{ r ∈ R : r.h.where = l.c.γ.σ ∧ r.h.when = receipt(l.c.m) \} // l.c.p refers to a problematic element
6         where the execution is recorded.
7         if r = 0 then
8             create a rule r
9             r.h.where = l.c.γ.σ
10            r.h.when = receipt(l.c.m)
11            Add r into R
12     Set body of r based on the recorded debugging commands (l.d)
13     return R

14 Function saveRuleToModel (HSM sm, execution rule r)
15     Let P1 – P11 refer to the problematic elements of sm
16     Let selTrans and selStates be the selected states and transitions by the rule extracted from the r.body
17     if selStates has one member ∧ r.h.where refers to a state in sm then
18         Let des be a state equal to the only member of selStates in sm and src be a state equal to r.h.where in sm
19         Let selTran be the first member of selTrans // selTrans has maximum one member since selStates has one
20         member and for a state, more than one transition cannot be selected
21         if selTran ∉ P10 then
22             t ← add_trans(src, des)
23         else
24             t ← selTran
25             t.act ← (r.body without select statement) + t.act
26             Set t.trig based on the receipt statements from r.h.when
27             Set t.guard based on the r.h.when by excluding the receipt statements
28     if r.h.where ∈ P6 then
29         t.guard ← t.guard ∧ (∨ ∀ t′ ∈ out_trans(t, src) guard(t'))
```

\{red, green, yellow, off\} and the selected transitions are \{t13\} and {} respectively. It then takes the following steps.

1) It checks if the rule selects only one state. This check is necessary, because the application of a rule that selects more than one state can make the resulting model nondeterministic. E.g., rule r6 in Listing 3 selects more than one state (red, green, yellow, off), and therefore saving this rule into the design model would require adding four transitions from state green into the mentioned states with the same trigger (off) and would cause nondeterminism. The function also checks if the where part of the rule explicitly refers to a state because otherwise, it is not clear which element in the design model should be fixed (line# 16).

2) It creates a transition (t) whose source is set to the where part of the rule and whose destination is set to the state that is selected by the rule if the rule does not address a not-takeable transition (P10 partialness). There is no need to add a new transition to fix a not-takeable transition (line# 17-22). Note that if the source and destination states of t are not contained in the same composite state, function add_trans adds required transitions and related entry-point and exit-point states to assure the transition does not cross the boundary of its parent state (see Def. 9).

3) It then sets the action of t based on the body of the rule. Note that since a not-takeable transition may already have actions. Therefore the action is appended to the body of the rule. The trigger of t is set based on the receipt statements in the when part of rules, and its guard is set based on the when part of the rule, excluding the receipt statements (line# 23-25).

4) Finally, if the rule handles the non-exhaustive guard of a choice point ch1, the guard of t is conjoined with the negation of the disjunction of the guards of all transitions leaving ch1, as calculated during the refinement (line# 26-27).

Note that when a rule is applied, it fixes the relevant partiality and there is no need to manually modify the model after its application, because the model is updated in a way that follows the semantics of the rules precisely, and respects all HSM well-formedness constraints (see Def. 9). Also, the algorithm only presents the application of an execution rule into the design model. Saving an interactive decision into the design model can be performed by saving it as an execution rule, which is then can be applied to the design model as discussed.

4.5 Tool Support (PMExec)

We have developed PMExec\(^1\) that embodies our approach and supports execution of partial UML-RT models. We used

\(^1\)https://moji1@bitbucket.org/moji1/partialmodels.git
the Epsilon Object Language (EOL) [36] to implement the transformation rules required for refining the models into executable models. EOL supports a set of instructions to create, query, and modify models. The part for the execution of the refined models (debugging probe) is implemented using C++, ANTLR [45], and the Boost C++ Library [46].

4.5.1 PMExec Features

In the following, we discuss the features of PMExec from the user point of view. When it is possible, the use of features is explained using the running example.

Setup and run

The PMExec is integrated into Papyrus-RT as an Eclipse plug-in and can be downloaded and installed from the PMExec repository. After installation, it can be used to run partial UML-RT models simply by defining a run configuration (i.e., an Eclipse run configuration) inside Papyrus-RT. The static analysis, transformation, code generation and build run automatically in the background without distracting the user. Upon successful execution, PMExec loads a UI as shown in Figure 8 as soon as the execution requires user input to continue the execution. The UI is split in two parts, a HSM view (1) of Figure 8 and a DBG console (2) of Figure 8. In the HSM view the user can see the HSM of the capsule where the current execution state is highlighted. In the DBG console the user can interactively issue commands to investigate and fix the execution problems. Some of the most important commands are discussed in the following in the context of the running example.

**View/select options** List the possible options to fix/continue the execution. E.g., the output of `view options` for the CTR when its execution is stuck in state yellow is shown in part 2 of Figure 8. Using the console, the execution can now be steered to any of the defined states inside the HSM. The command `select` allows users to select one of the possible options, e.g., `select state red` steers the execution to state red.

**Simple expressions** Similar to scripting languages (e.g., Python’s interactive console), PMExec allows the user to issue simple expressions (e.g., arithmetic expressions) and statements (to, e.g., define a new variable, or change/view variable values). This allows the user to investigate and modify the execution before deciding how to advance the execution. E.g., `x=5+1` creates a new variable `x` and sets its value to 6. Defined variables can help the user record certain properties of the execution and define complex debugging and testing scenarios. Once defined, they can be used till the end of the execution.

**Communication commands** To allow the user to fix
issues concerning the missing inputs (P7), three communication commands are provided: inject, send, and reply. The command inject sends a signal to a capsule to start a debugging session, the command send sends messages on behalf of the capsule being debugged to the connected capsules, and the command reply sends an incoming message back on the same channel it has been received. E.g., in the context of running example, no behavior is defined for the component UC. Thus, the execution of the CTR will get stuck in state off and the overall execution of the system will be deadlocked. The user can fix the problem by using the following communication command (1) ‘inject uc’ to start a debugging session with capsule UC. Note that the refinement fixes the behavior of capsules even with no defined behavior. (2) ‘send message on’ to send message on to the CTR where it will trigger a transition to turn on the red light.

Batch execution PMExec supports a batch execution mode which allows users to provide inputs using a script of execution rules. The Listing 3 is an example of an execution script in the context of the running example.

1. The rule r1 steers the execution to state red when a message timeout is received while in state yellow.
2. The rule r2 replies to any received message using a random message and then moves the execution to a random state. The rules with header ‘*’ are only selected when no other rule matches in the current execution context. Note that having only one rule similar to r2 is enough for the random execution of any partial model using PMExec.

Save command To save users’ decisions which are provided interactively as execution rules, users can view the history of the execution using ‘view exec’. The output shows all previous decisions (inputs), each of which is given a unique id. Then, the user can use save command (‘save input id’) to save the input with the related id as an execution rule. Also, to save an execution rule into the design model, users can use ‘save rule id’ that saves the rule with the related id into the design model. Note that in both cases (save input/rule), more than one input/rule can be processed by providing more than one id.

5 Validation
This section explains the validation of our approach which consists of three parts: online survey, formal validation and empirical evaluation. The goal of the online survey was to collect the opinions of MDE researchers and practitioners w.r.t. whether or not (1) the execution of partial models is a necessary and useful technology in the context of MDE, and (2) our approach is helpful to address the execution of partial models. The formal validation is concerned with the properties of the refinement approach and shows formally how the applied refinement does not change the behaviour of the original specification of the models but fixes the problems of lack of reachability and progress. The empirical evaluation is concerned with the applicability of the approach in practice. It applies our approach to several partial UML-RT models in different scenarios and evaluates the performance and overhead. In the following, we discuss each part in detail.

5.1 Online survey
5.1.1 Survey Design
The survey" consists of two steps: First, we ask participants who are MDE researchers or practitioners to view a short demonstration video (5 minutes) of PMExec to familiarize them with the execution of partial models. Note that the video does not demonstrate the automation features as discussed in Sec. 4.4, since the features were inspired by the suggestions of the participants. Second, we ask them to answer 15 questions classified into three groups: demographic (4 questions), general questions regarding the execution of partial models (5 questions), and specific questions concerning our proposed approach (6 questions). 7 questions are 5-level Likert scale questions [47] (Strongly disagree, Disagree, Neutral, Agree, Strongly agree), 6 questions are multiple choice questions, one question is asking for the email address of the participant (email question), and one question is an open-ended question. All of the questions except the open-ended and email question are mandatory. However, participants are allowed to provide other answers rather than the choices or scales presented to them. Note that, providing an email address is optional to allow participants to be anonymous in case they want to provide negative feedback.

5.1.2 Participants
We approached MDE practitioners and researchers in person at the MODELS (2019) conference, as well as by email and social media and asked them to participate in the survey. Our efforts resulted in 39 participants whose demographic data is shown in Figure 9. More than 81% of

![Listing 3: An example script of the execution rules in the context of the TrafficLight](image)

![Figure 9: Survey participants’ occupation and experience with MDE](image)

3https://tinyurl.com/xyv8embf
The execution of incomplete (partial) models is a necessary feature that MDD tools should support. The fact that existing MDD tools do not allow execution of partial models has a negative impact on when and how MDD developers debug and test models. The demonstrated solution is a promising first step toward supporting the execution of partial models. In general, the manual completion of models will be easier than the execution of models using the demonstrated solution. The proposed process for the execution of partial models is easy to understand and use, assuming that its implementation and tool support has a sufficient degree of maturity.

Figure 10: Participants’ opinion concerning the execution of partial models and our proposed solution

![Chart showing participants' opinion]

| Activity                                    | Strongly agree | Agree | Neutral | Disagree | Strongly disagree | Others |
|---------------------------------------------|----------------|-------|---------|----------|-------------------|--------|
| Early debugging of system                   | 6              | 12    | 20      | 18       | 1                 | 8      |
| Interactive debugging                       | 6              | 4     | 18      | 8        | 2                 | 4      |
| Agile software development                  | 6              | 4     | 18      | 8        | 2                 | 4      |
| Teaching a modeling language to new users   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Collaborative development                   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Learning a new modeling language            | 6              | 4     | 18      | 8        | 2                 | 4      |
| Exploration of different design decisions   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Improving user experience of MDD tools      | 6              | 4     | 18      | 8        | 2                 | 4      |
| Mocking and unit testing                    | 6              | 4     | 18      | 8        | 2                 | 4      |
| Agile software development                  | 6              | 4     | 18      | 8        | 2                 | 4      |
| Early debugging of system                   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Interactive debugging                       | 6              | 4     | 18      | 8        | 2                 | 4      |
| Agile software development                  | 6              | 4     | 18      | 8        | 2                 | 4      |
| Teaching a modeling language to new users   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Collaborative development                   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Learning a new modeling language            | 6              | 4     | 18      | 8        | 2                 | 4      |
| Exploration of different design decisions   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Improving user experience of MDD tools      | 6              | 4     | 18      | 8        | 2                 | 4      |
| Mocking and unit testing                    | 6              | 4     | 18      | 8        | 2                 | 4      |
| Agile software development                  | 6              | 4     | 18      | 8        | 2                 | 4      |
| Teaching a modeling language to new users   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Collaborative development                   | 6              | 4     | 18      | 8        | 2                 | 4      |
| Learning a new modeling language            | 6              | 4     | 18      | 8        | 2                 | 4      |

Figure 11: Participants’ opinion about which activities the execution of partial models can facilitate

![Chart showing participants' opinion]

The usefulness of our approach As shown in Figure 10, all of the participants except two of them perceive our approach as a first promising step toward addressing the execution of partial models. Also, 84.4% of the participants either strongly agree (15.4%) or agree that the current approach can be useful for MDD users, assuming that the approach has good tool support. 86.4% of the participants prefer to use both interactive and scripting methods for providing input, depending on the execution scenarios. 69.2% of participants are of the opinion that the execution of models by providing input through scripts is easier than through a manual completion of models. However, 15.4% of participants have the opposite view.

In addition, we received valuable and constructive responses to the open-ended question as discussed in the following.

1) As quoted in the following, one of the participants pointed out correctly that our approach only is applicable to modeling languages with step-based execution semantics. “This can likely work well with behavioral models such as state-charts or business process models, but I wonder about whether the value proposition also covers non-behavioural models such as goal models, where “execution” is not a sequence of events but a set of values or initial decisions”

2) As discussed, the video does not demonstrate the automation features as mentioned in Sec. 4.4, since the following suggestion inspired the features.

“The script option sounds like it does not much improve on manual fixing/completion of models. I suspect that it may prove more useful if: (a) the script is automatically generated (as a user option) during an interactive session and then applied (as a user option) on subsequent runs. (b) used as a means of automatically modifying the incomplete model — again, as a user option.”

3) As quoted in the following, one of the participants suggested an interesting extension to the work by augmenting the semantics of modeling language to support the execution in the presence of holes that are specified with certain notations. We agree with the participant. However, we left addressing this extension to future work.

“The partiality of the model in the demo seems to pertain only to violated statically checkable constraints such as whether a state is exitable/reachable. This would certainly help modellers. Another type of partiality is the presence of “holes”, i.e. properties not being filled in (cf. Scala’s “???”), not resolved, etc. I think it’s a good idea in general to augment semantics of a modelling language that they stay defined (but possibly defined in terms of a fault mode) in the presence of missing model parts. This is akin to interpret...
every .operator as ?.operator (Kotlin, TS, etc.) and propagate nulls/undefined in a as meaningful as possible manner."

4) Not surprisingly, as quoted in the following, two of the participants have constructive feedback concerning the
tooling issues. However, in this work, our main focus is the
creation of a prototype as proof of concept, and improving
tooling is left to future work.

"I found your presentation of the context to be rather technical.
For example, at 2 minutes in the video you showed the output for
the empty UserConsole. There you presented one option how I
could continue. I think you might have a technical reason to call
the states Init_State_3 and New_State_2 but to me as a user
it is unclear what these numbers mean (any why a state that
is not even created yet?) would have a lower number than the
initial state you already generated). But I really liked, that you
highlighted the current state in the visual representation of the
diagram."

Overall, based on the participants’ opinions, we can con-
clude that while our proposed approach is a step in the right
direction, it is not the final solution (i.e., it has limitations).
Still, further research and development are required in this
context, some of which will be discussed in Section 6.

5.2 Formal Validation

We use $\mathfrak{R}^{HSM}$ to refer to the result of applying Algorithm 2
on an HSM and call it the RefinedHSM of the HSM. In
the following, first, we define the simulation relationship
between LTSs, and then discuss the properties of $\mathfrak{R}^{HSM}$.

5.2.1 Behavioural Preservation

Definition 20. (Simulation Relation) Let $L_1 = \langle \Gamma_1, \mathcal{A}_1, \gamma_{10}, \mathcal{Q}_1, \rightarrow_1 \rangle$ and $L_2 = \langle \Gamma_2, \mathcal{A}_2, \gamma_{20}, \mathcal{Q}_2, \rightarrow_2 \rangle$
refer to LTSs of two HSM, $HSM_1$ and $HSM_2$ respectively
(LTSs are discussed in detail in Def. 11). We write $L_1 \leq L_2$ and say $L_2$ simulates $L_1$ if there is a binary relation $R \in \Gamma_1 \times \Gamma_2$ with the following two properties.

Start property: $\gamma_{10} \neq \emptyset \implies (\gamma_{10}, \gamma_{20}) \in R$. Note that, in
the execution of HSMs only one initial state is allowed.

Step property: Let $(\gamma_1, \in \Gamma_1, \gamma_2 \in \Gamma_2) \in R$.

For all $\gamma_1 \in \Gamma_1$ and $a$, whenever $\gamma_1 \stackrel{a}{\rightarrow} \gamma_1'$
there exist $\gamma_2' \in \Gamma_2$ such that $\gamma_2 \stackrel{a}{\rightarrow} \gamma_2' \land (\gamma_1', \gamma_2') \in R$.

The step property implies that when $(\gamma_1, \gamma_2) \in R$, any execution step started from $\gamma_1$ can be matched by an
execution step started from $\gamma_2$ such that they both execute
the same actions and reach configurations that again are in
relation $R$.

Simulation implies trace containment, i.e., every se-

Proposition 1. Assuming that $L_o$ and $L_r$ receive the same
sequence of messages ($Q_1 = Q_r$) and users do not issue
any debugging commands during the execution of $\mathfrak{R}^{HSM}$,
the relation $R$ (as defined above) is a simulation relation,

Lemma 5.1. For message $\mu$ and basic state $s$, if function
next_t(s, $\mu$)) (see Table 1) returns transition $t$ in the context
of HSM, then it returns the same transition ($t$) in the context
of $\mathfrak{R}^{HSM}$.

Proof. (Lemma 5.1) According to Algorithm 2, the refine-
ment applies the following changes to the basic states: (I)
Add a transition from a basic state to dec_p. The trigger of
this transition is set to in(c) \ handled(s_b) in order to
not affect the existing transitions. This ensures that if a
transition of HSM can be triggered by message $\mu$, it still
can be triggered by the same message in $\mathfrak{R}^{HSM}$ and next_t
in both cases returns the same transition. (II) The source of
not-takeable transitions is changed to dec_p. next_t never
returns a not-takeable transition, thus this change does
not affect function next_t. (III) A transition is added from
dec_p to isolated states. Function next_t never returns an
incoming transition to a state as the result. Thus, this change
does not affect next_t either. Based on (I), (II), and (III) the
proof of this lemma is complete.

Lemma 5.2. For basic state $s$, if function dead(s) (see
Table 1) returns false in the context of HSM, then it also returns
false for state $s$ in the context of $\mathfrak{R}^{HSM}$.

Proof. (Lemma 5.2) No state or takeable transition is re-
moved by the refinement. Thus if state $s$ or one of its an-
cestors (parents(s)) has a takeable transition (t) that prevents
$s$ from being dead, the same transition also exists in
$\mathfrak{R}^{HSM}$.

This completes the proof of this lemma.

Proof. (Proposition 1) To prove that $R$ is a simulation rela-
tion, first, we need to show that the start property holds
which includes the following two cases.

- The initial state of HSM is missing. This case is trivial,
since without initial state, the execution of HSM cannot
start (see Def. 11) and $\gamma_{00} = \emptyset$. Thus, the start property
holds for this case.

- HSM contains the initial state (i.e., $\gamma_{00} \neq \emptyset$). In this
case we need show that $(\gamma_{00}, \gamma_{r}) \in \mathcal{R}$ where $\gamma_r$
is the initial configuration of $\mathfrak{R}^{HSM}$. (I) According to
(lines # 5-6 of Algorithm 2), when the original HSM
contains the initial state init, the refinement keeps the
same initial state in the refined HSM (i.e., the initial
states of $\mathfrak{R}^{HSM}$ and HSM are equal to init). According to
evolution semantics of HSM (see Def. 11), the execution
of HSM starts from the initial configuration where its current
state is set to the initial state of the HSM. Thus,
there is an initial configuration of $\gamma_r \in \Gamma_r$ in which
the current state is equal to init i.e., $\gamma_{r0} = \gamma_{r0}$. (II)
$\gamma_{00}, $H = \gamma_{r0} \mathcal{H}$ because the history is set to empty
for the initial configuration (see Def. 11). (III) Similarly,$\gamma_{00} \mathcal{E} = \gamma_{r0} \mathcal{E} \setminus \mathcal{R}^c$, because the initial values of vari-
ables are set to default values and the refinement does
not remove any existing variable. Based on (I), (II), and (III) we can conclude that $(\gamma_{00}, \gamma_{r0}) \in \mathcal{R}$ and conclude
that the start property of simulation holds for this case as well.

Second, we have to show that the step property holds for any \((\gamma_0 \in \Gamma_o, \gamma_r \in \Gamma_r) \in R\) which includes two main cases according to the execution semantics of HSM (see Def. 11).

- \(\gamma_0\) is a stuck configuration, i.e., no execution step can originate from it. Thus, the step property holds for this case.
- \(\gamma_0\) is a not stuck configuration. Based on the execution rules (see Def. 11), this case includes 4 sub-cases: (1) the current state \((\gamma_0, \sigma)\) is a pseudo-state of kind initial, entry-point, exit-point, or junction-point (Rule-1), (2) the current state is a basic state (Rule-4), (3) the current state is a history state (Rule-6), and (4) the current state is a choice-point (Rule-8). Proof of all sub-cases is similar and here we only prove sub-case (2).

Let us assume that \(\gamma_0, \sigma \in S_o\) \((\gamma_o \in \Gamma_o, \gamma_r \in \Gamma_r) \in R\) and an execution step \(s_{t_o} = (\gamma_o \rightarrow \sigma)\) is taken. First, we have to show that an execution step \(s_{t_r} = (\gamma_r \rightarrow \gamma_r')\) can be started from \(\gamma_r\) that executes the same actions as \(s_{t_o}\). To prove the existence of \(s_{t_r}\), we have to show that the following condition holds (see Rule-4, Def. 11).

\[
Q_r \neq \emptyset \land \gamma_r, \sigma \in S_o \land \neg \text{dead}(\gamma_r, \sigma) \land \\
\exists t \in T \mid t = \text{next}_t(\gamma_r, \sigma, \text{head}(Q_r))
\]

(I) Definition of \(R\) and assumption \(\gamma_o, \sigma \in S_o\) imply that \(\gamma_r, \sigma \in S_o\). (II) \(Q_o \neq \emptyset\) because the execution step \(s_{t_o}\) is not possible with an empty queue (see Rule-4, Def. 11).

Also, \(Q_o = Q_r\) based on the assumption of the proposition. Thus, \(Q_r \neq \emptyset\). (III) \(\neg \text{dead}(\gamma_r, \sigma)\) holds, because without that execution step \(s_{t_o}\) is not possible. Thus, based on Lemma 5.2 \(\neg \text{dead}(\gamma_r, \sigma)\) holds. (IV) First, \(\exists t \in T \mid t = \text{next}_t(\gamma_r, \sigma, \text{head}(Q_o))\) holds, otherwise the execution step \(s_{t_o}\) is not possible. Second, \(Q_r = Q_o\) implies that \(\text{head}(Q_r) = \text{head}(Q_o)\). Third, \(\gamma_o, \sigma = \gamma_r, \sigma\). Based on the statements above and Lemma 5.1, we can conclude that the last part of the above formula \(\exists t \in T \mid t = \text{next}_t(\gamma_r, \sigma, \text{head}(Q_r))\) holds. Based on I, II, III, and IV we conclude that execution step \(s_{t_r}\) exists.

Next, we have to show that \(s_{t_r}\) and \(s_{t_o}\) execute the same sequence of actions. According to Rule-4 (see Def. 11), definition of relation \(R\), and Lemma 5.1, both \(s_{t_r}\) and \(s_{t_o}\) execute the same actions, i.e., \(\text{exit}(t, \text{src}), \text{exit}(t, \text{act})(t), \text{entry}(t, \text{des})\), where \(s = \gamma_0, \sigma = \gamma_r, \sigma, \mu = \text{head}(Q_o) = \text{head}(Q_r)\) and \(t = \text{next}_t(s, \mu)\).

Finally, we have to show that \((\gamma_0', \gamma_r') \in R\). (I) We have already shown that \(\text{next}_t(t) = \text{next}_t(t)\) returns the same result for both current states \(\gamma_0, \sigma\) and \(\gamma_r, \sigma\). Thus, \(\gamma_0, \sigma = \gamma_r, \sigma\) with \(t, \text{des}\) as active state where \(t\) is the result of \(\text{next}_t(t)\) (Rule-4). (II) Similarly, \(\gamma_0, \mathcal{H} = \gamma_r, \mathcal{H}\) which are set to \(u, h(t, \text{des}, \mathcal{H})\). \(\mathcal{H}\) refers to history of \(\gamma_0\) and \(\gamma_r\) which are equal (Def. 21). (III) Variables are only changed by the execution of actions. Since the same sequence of actions is executed by \(s_{t_0}\) and \(s_{t_r}\), and \(\gamma_0, \mathcal{E} = \gamma_r, \mathcal{E} \setminus \mathcal{R}\), we have \(\gamma_0, \mathcal{E} = \gamma_r, E \setminus \mathcal{R}\). Based on (I), (II), and (III) we can conclude that \((\gamma_0', \gamma_r') \in \Gamma_o, \Gamma_r \in R\). Thus, the proof for sub-case (2) is complete.

The other sub-cases can be proven similarly, and we conclude that the relation \(R \in \Gamma_o \times \Gamma_r\) is a simulation relation and by that execution of \(R^{HSM}\) simulates the execution of HSM.

While \(R^{HSM}\) preserves the behavior of the original HSM, it also never gets stuck and provides useful features to steer the execution to relevant states and debug the execution of the HSM, assuming the required inputs are provided. In the rest of this section, we discuss the important properties of \(R^{HSM}\).

5.2.2 Reachability of the execution

Proposition 2. (Reachability of States) Assume \(L_r = (\Gamma_r, A_r, \gamma_0, Q_r, \rightarrow_r)\) is the execution semantics of \(R^{HSM}\). Let \(\gamma\) be the current configuration of \(L_r\), where \(\gamma, \sigma \in S_0\). By injecting a \(\text{dbg}\) message, the execution can be steered by a finite number of execution steps to any configuration \(\gamma'\) in which the current state is any state except initial, choice-points, and composite (implicit history) states, assuming that proper inputs are provided.

Proof. (Reachability of States) Let \(\sigma\) be the current state of configuration \(\gamma\), and \(\sigma'\) be the current state of configuration \(\gamma'\) to which we want to steer the execution. Proving that \(\gamma'\) is reachable by taking a finite number of execution steps, includes three cases. (I) Both states \(\sigma\) and \(\sigma'\) have the same parent, i.e., \(\text{parent}(\sigma) = \text{parent}(\sigma')\). In this case, based on the execution semantics of HSMs, injecting a \(\text{dbg}\) message starts an execution step that moves the execution to the same state \(\gamma'\) as the current state \(\sigma\). The execution can be steered to \(\gamma'\) by providing the required input. (II) \(\text{parent}(\sigma) \in \text{parents}(\sigma') \land \text{parent}(\sigma) \neq \text{parent}(\sigma')\). In this case, after the execution reaches the first \(\text{dec}_p\), it then can be moved using a series of \(\text{to}_\text{child}\) and \(\text{from}_\text{parent}\) transitions (lines# 20-26 of Algorithm 2) until reaching \(\gamma'\) whose current state is \(\sigma'\). (III) \(\text{parent}(\sigma') \in \text{parents}(\sigma) \land \text{parent}(\sigma) \neq \text{parent}(\sigma')\). In this case, after the execution reaches the first \(\text{dec}_p\), it can then be moved using a series of \(\text{to}_\text{parent}\) and \(\text{from}_\text{child}\) transitions (lines# 20-26 Algorithm 2) until reaching \(\gamma'\) whose current state is \(\sigma'\). Based on (I), (II), and (III), the proof of Proposition 2 is complete.

Proposition 3. (Reachability of Transitions) Let \(\gamma\) be the current configuration of \(L_r\), where \(\gamma, \sigma \in S_0\). By injecting \(\text{dbg}\) and related messages, a sequence of execution steps can be taken to execute the action of any transition, except for initial transitions and transitions starting from choice-points.

Proof. (Reachability of transitions) Based on the execution semantics of HSMs a prerequisite for the execution of the action of transition \(t\) is to move the execution to a configuration \(\gamma\) whose current state is (1) the source state of transition \(t\), or (2) a basic state inside the composite state which is the source of transition \(t\) (when a transition \(t\) starts from a composite state). According to Proposition 2,
this can be done by injecting a \textit{dbg} message and providing proper inputs. Thus, we have to show that after reaching the source state of the transition \( t \) according to (1) or (2), an execution step can be taken to execute the action of the transition which includes five cases based on the source state of transition \( t \): (1) pseudo-state except for choice-points and initial states, (2) basic state, (3) composite state, (4) choice-points, (5) initial state.

(1) The proof for Case-1 is trivial. According to the Rule-1 (see Def. 11), the execution step is taken from these states if there is an outgoing transition originating from them. Thus, an execution step can be taken that executes the action of transition \( t \).

(II) The proof of case-2 and case-3 is similar to Case-1 assuming proper input messages are provided (trigger of transition \( t \)). As we discussed in Sec. 4.3.1, we provide a message injection feature that simplifies this.

(III) Case-4 is not part of the proposition, because it is not possible to ensure that the transition \( t \) is executed due to its guard expression. Any buggy guard statement can prevent the execution of the transitions originating from a choice-point.

(IV) Case-5 is not part of the proposition. There is no way for the execution to re-visit the transition starting from the initial state, except by restarting the execution. Based on (I) and (II), proof of Lemma 3 is complete.

\[ \square \]

5.2.3 Progress of the execution

\textit{Proposition 4. (Progress of the Execution) The execution of \( \mathcal{R}_{HSM} \) never reaches a stuck configuration assuming proper inputs are provided.}

\textit{Proof. (Sketch) As we discussed in Sec. 4.4, the execution gets stuck due to two groups of issues: (1) Missing/problematic specification. (2) Missing input messages. All of the elements in group (1) are fixed by the refinement. Also, \textit{dbg} and other relevant messages can be injected by users which prevents a component from getting stuck because of missing inputs. Here, we do not present a detailed proof, but it can be performed similar to the previous proofs. \[ \square \]}

5.3 Empirical Evaluation

This section details experiments we conducted to assess the performance and overhead of our approach. In the following, we describe use-cases, evaluation metrics, experiments, and results.

5.3.1 Use-cases

To perform experiments, several use-cases are used. As shown in Table 2, models have different complexities that range from simple models containing 11 states to models with 350 states. Simple models include the Car Door Central Lock system and the Digital Watch. The Car Door Central Lock system is a control system for locking and unlocking car doors. The Digital Watch is an implementation of classical digital watch, which is described in [49].

The Parcel Router [50], [51] is an automatic system where tagged parcels are routed through successive chutes and switches to a corresponding bin. The system is time-sensitive and jams can appear due to variations in the time required by a parcel to transit through the different chutes. It checks for potential parcel jams, and prevents parcels from being transferred from one chute to another until the next chute is empty. The simplified version ignores jams.

The Rover system model [52], [53] allows an autonomous robot to move in different directions. It is equipped with three wheels, driven by two engines. It can move forward, move backward, and rotate. Additionally, it is equipped with several sensors, such as temperature and humidity sensors, to collect data from the environment, and an ultrasonic detection sensor, to detect and avoid obstacles.

The FailOver system [54], [55] is an implementation of the fail-over mechanism. It involves a set of servers processing client requests. To meet high availability, the system supports two replication modes, passive and active [56]. In passive replication, one server component works as the master, handling all the client requests while backup servers are mainly idle, except for handshake operations. Whenever a malfunction occurs, resulting in a failure of the master server, a backup server is ranked up as the new master. In active replication, client requests are load-balanced between several servers.

The Debuggable FailOver system is a debuggable version of the FailOver system, which is generated using MDebugger [13]. The complexity of this model is high, and allows us to check that the refinement and analysis time do not skyrocket when the model size grows exponentially.

5.3.2 Evaluation Metrics

We formulated the following metrics to assess the practicality of our approach.

\textbf{Metric 1 (Performance of Analysis and Refinement).} We use model analysis and transformation to fix partial models for the execution. The analysis and refinement are the core of our approach, and their performance is a crucial metric for the practicality of our approach. Thus, this metric measures the time required for the analysis and transformation of models.

\textbf{Metric 2 (Overhead of refinement).} As discussed, the refinement adds certain elements to fix the execution of partial models. These new elements increase the complexity of the models in terms of the number of components, states, and transitions. This metric first measures how the complexity of refined models changes in comparison with the original ones. The refined model is created temporarily before execution, and is only used for code generation. Thus, this metric also measures the code generation time for original and refined models, in order to determine the side effects of the increased model size.

\textbf{Metric 3 (Performance of the debugging probe).} When executing the partial models, the execution of HSM is passed to the debugging probe, to read and apply user input. In the interactive model, there is always a delay imposed by users in the loop, and the performance is not an important factor. However, in the batch mode, it is essential that the debugging probe efficiently selects and applies the execution rules. This metric measures the time required to load, select, and parse rules.
5.3.3 Experiments

In the following, we discuss the experiments used to calculate the metrics.

Measuring the performance of static analysis and model transformation (EXP-1). To effectively measure the performance of analysis and transformation, first we used Epsilon [36] to create nine versions of each model (partial versions), listed in Table 2 by removing 10%-90% of their elements, randomly. This results in 60 models (including the original ones). In the rest of this section, we refer to these versions by merely mentioning the model name appended with the percentage of removed elements (e.g., Rover%10 refers to a version of the model of the Rover system that has 10% of its elements removed randomly). Also, we use the percentage without a model name to refer to all models with the same level of missing elements (e.g., 10% refers to model versions of all use-cases that have 10% of their elements missing).

Second, we ran the model analysis and refinements 20 times against the original and their partial versions, with a configuration in which all components are assumed to be partial. The rationale for the configuration is to measure the performance in the worst-case scenario. As discussed, the refinement and analysis of a partial components is much more expensive than the complete and absent/ignored components. No refinement is applied on complete components, and the behaviour of an absent/ignored component is replaced with a simple generic state machine. We recorded the time required for analysis and refinement, which is a reflection of their performance in the worst-case scenario. We also saved the partial and refined versions of the model that are used in EXP-2.

Measuring the overhead of the refinement (EXP-2) First, we measure the complexity of the models, and their refined version resulting from EXP-1 in terms of the number of components, states, and transitions. Second, we generated code from them 20 times, and recorded the execution time of the code generation. This experiment reveals how the model complexity is increased when applying refinement, and what the effects of this increase are on the code generation.

Measuring the performance of execution rule selection and application (EXP-2) To measure the loading/selection time of the execution rules, we generated 10,000 rules with 100 Lines of Code (LOC) in the context of the ABM system which is a controller of an Automatic Banking Machine (ABM) designed using UML-RT. We performed a test that loads the rules in four scenarios, in which 10, 100, 1000, 10,000 rules are used accordingly. We recorded the loading time in each scenario. Then, using a test program, we called the rule selection method for the random context based on the ABM system 1000 times, and measured the rule selection times.

To measure the time required to apply execution rules, we randomly generated four execution rule bodies, containing 1, 10, 100, 1000 lines in the context of the ABM system. We ran a test to measure the time required to parse the rule bodies, 20 times. We did not measure the execution time of the rules’ body, since their execution time is dependent on their content, which is controlled by users. The debugging probe executes the body of the rules as they are.

5.3.4 Setting and Reproducibility of Experiments

We used a computer equipped with a 2.7 GHz Intel Core i5 and 8GB of memory, for all experiments, which is typical development PC. The experiments are automated using bash scripts. The scripts and models are publicly available at [44] and can be used to repeat our experiments. Note that we intentionally used a standard computer comparable to those used by developers, rather than more powerful hardware, because the debugging of partial models typically needs to be carried out daily.

5.4 Results

Metric 1 (Performance of analysis and refinement). Based on the result of EXP-1, the Analysis Time and Transformation Time columns of Table 2 show the median, maximum and minimum time required to analyze and transform the ten versions of each use-case. For the largest model (Debuggable FailOver), the medians of analysis and transformation are less than two and 12 seconds, respectively. It is therefore safe to conclude that the performance of analysis and refinement is reasonable even when the configuration of all components is set to partial which is the worst-case configuration. Typically, the execution of partial models is focused on executing specific components, and the rest of the components are assumed to be complete or absent/ignored which is less expensive to analyze and refine.

Figure 12 shows number of elements in P1-P11 except P10 for the different versions (Orig. and 10%-90%) of the Debuggable FailOver system. The number of elements in P5, P6, P7, P8, P11 decreases as the number of removed elements increases, i.e., the number of elements in these

| Model                | Orig. Model Complexity | Analysis Time (ms) | Transformation Time (ms) |
|----------------------|------------------------|--------------------|--------------------------|
|                      | C  S  T                | Median  Max.  Min. | Median  Max.  Min.       |
| Car Door Central Lock| 5  11  15              | 418  925  250      | 2024  3704  782          |
| Digital Watch        | 9  47  57              | 717  1535  322     | 5219  11126  2225        |
| Parcel Router        | 8  14  25              | 418  1674  220     | 2877  5305  1279         |
| Rover                | 6  16  21              | 604  925  313      | 3062  5001  1254         |
| FailOver             | 7  31  43              | 739  2247  257     | 4523  10416  1685        |
| Debuggable FailOver  | 8  350  620            | 1694  8454  347    | 13376  35000  1887       |

C: Component, S: State, T: Transition, Orig.: Original
sets are highest for original models. This is because of the overestimation for extracting these sets which is based on the numbers of elements in the HSM. For example, \( P11 \) includes all basic states of the HSM. Thus removing more elements (states and transitions) in the HSM causes a decrease in the number of elements in \( P11 \). However, the number of elements for \( P1, P2, P3, P4, P9 \) reaches its maximum between versions 30%- 60%, because in these cases the removed elements cause a maximal amount of issues for the remaining elements of the HSM. This number then decreases in the subsequent versions when more and more of these remaining elements are also removed. Note that the number of elements in \( P10 \) is not included in the figure, because we only remove states and transitions from the original model. Thus, the number of elements in \( P10 \) does not change between versions.

**Metric 2 (Overhead of the refinement).** Based on the results of EXP-2, Fig. 13 shows the percentage of added elements (states and transitions) to the original models and their partial versions, during the refinement (i.e., the number of the added element divided by the number of elements before refinement multiplied by 100). Not surprisingly, the number of added elements increases as the number of removed elements from models increases. Removing more elements introduces more problems for the execution, which in turn requires more elements to be added to fix these problems.

The percentage of added states is between 20% (the median of the percentage of added states for original versions of models) and 216% (the median of the percentage of added states for model versions with 90% removed elements). The percentage of added transitions is between 67% (median of the percentage of added transitions for the original model versions) and 300% (median of the percentage of added transitions for model versions with 90% removed elements). Note that the percentage of added transitions for the versions with 90% removed elements is almost fixed (300%) because almost all are removed and the refinement always adds almost the exact same elements to refine them similar to absent/ignored components. The percentage of added transitions is higher than the percentage of added states, since many of the execution problems are fixed by adding transitions. Also, the number of components increases only by one (i.e., the \( \text{dbg} \_\text{agent} \) component). We argue that these overheads are reasonable compared to the capabilities provided by the refined models, for the following reasons:

- In most of the cases, the refinement adds elements when there is a missing/problematic element and there is no other way to fix them using existing tools and techniques. Our approach simply automates the fix for problematic elements. Otherwise, users have to fix them manually, which is time-consuming and tedious.
- The refined models are temporary models, which are
only used for code generation. Thus, the overhead of added elements has no side effect except for the code generation. The result of the second part of EXP-2 shows that the code generation of the refined model is only 8% slower than the code generation for original models, which is calculated based on the median of the time for code generation from refined models, divided by the time for code generation from the original models.

- As discussed, the experiments are performed using the worst-case configuration, and their results reflect the maximum costs of our approach. Otherwise, using realistic configurations, which focus on the execution of certain components, can even decrease the complexity of the refined models with respect to the original models. E.g., the refinement of the Debuggable Failover system by setting the completion level of the Client component to partial and the level of the other components to absent/ignored results in a refined model with 138 states and 326 transitions, which is almost 50% smaller than the original model!

**Metric 3 (Performance of the debugging probe).** Based on the result of EXP-3, Table 3 shows the time required for loading and selecting rules by the debugging probe. The selection time is the median time of rule selection for 1,000 times. The loading of rules occurs only once the execution of the system starts. During the loading, the script of execution rules is loaded and parsed. The parsing in this phase only parses the rules’ headers, and saves their body as text. As shown in Table 3, the debugging probe can load 10,000 rules in less than a second, which is acceptable, because it happens only once.

As discussed in Sec. 4.3.1, in batch mode execution, the debugging probe must select an applicable rule from the defined rules whenever the execution reaches the decision points. As shown in Table 3, the rule selection time is negligible (less than a millisecond), and it is, therefore, safe to conclude that rule selection performance is acceptable.

When an execution rule is selected, the debugging probe parses the rule’s body and executes it. Thanks to ANTLR [45], the parsing time of the rule’s body has reasonable performance. Rule bodies with 1-1000 LOC can be executed in less than a second (the median execution time for a rule body with 1000 LOC is 550 milliseconds).

According to the results mentioned above (i.e., acceptable performance of analysis, refinement, and debugging probe and reasonable overhead of the refinement), we conclude that our approach is a practical approach for the execution and debugging of partial models.

### 6 Discussion

In the following we discuss issues with the input-driven execution of partial models, alternative solutions for the refinements of partial models, and threats to the validity of this work.

#### 6.1 Issues with the input-driven execution

Since the execution rules are defined using a scripting language, it may contain bugs similar to any other scripting language. Generally, there is no solution to this problem, and to mitigate this issue partially, our refinement method guarantees behavioral preservation (see Sec. 5.2). Therefore, it cannot introduce new bugs into the completed part of the models. Also, to help users when the script is buggy, the execution engine switches back to interactive mode and allows users to provide a correct input. Finally, providing proper tooling such as a high-quality editor for writing and validating scripts can mitigate the challenge of correct script authoring.

#### 6.2 Alternative refinement solutions

Note that the proposed refinement (see Sec. 4.4) approach is devised experimentally by experimenting with and evaluating possibly many different solutions. In Section 5, we discussed the correctness of our refinement approach concerning the relevant constraints (see Sec. 3). We also showed that our approach has reasonable performance and overhead for the refinement of partial models. However, at this stage, we do not claim that our refinement approach is the optimal solution, and alternative and even better refinement approaches can be proposed, especially if certain trade-offs or assumptions are made. For example, the refinement can only focus on fixing specific problems rather than addressing all of them depending on the users’ needs, e.g., refining only elements that participate in the lack of progress can be simpler and faster than our current approach. Nevertheless, the proposed refinement is comprehensive and can be used as a reference method to devise more specialized methods targeting more specific problems.

#### 6.3 Threats to the Validity

**Internal threats.** (1) To evaluate this work, we use generated models rather than using real partial models. Thus, the results of our evaluation may not be generalized to real partial models. To mitigate this issue, we tried to generate models with a wide range of partialness over several case studies to make sure they are representative of typical partial models. Also, we used a worst-case configuration for the evaluation. (2) The implementation of our approach is not trivial, and therefore our implementation may have bugs. To mitigate this problem, we rely on well-known tools and frameworks, such as EMF and Epsilon. We also have performed a thorough test and validation of our implementation. (3) The online survey participants viewed only a short demonstration video to familiarise themselves with the execution of partial models and our proposed approach. We partially mitigate this issue by carefully designing the video and targeting the MDE experts as participants, most of them already aware of the problems surrounding the execution of partial models.

| Rule Sizes | LOC of Rules | Loading time (ms) | Selection time (ms) |
|------------|--------------|-------------------|---------------------|
| 10          | 100          | 3                 | 0.006               |
| 100         | 100          | 13                | 0.006               |
| 1000        | 100          | 96                | 0.006               |
| 10,000      | 100          | 950               | 0.010               |
(4) Our study may be designed in a way that, inadvertently, steers participants towards specific answers. To mitigate this issue, the participants are allowed to provide other answers rather than what is presented to them. Also, providing an email address is not mandatory to enable participants to be anonymous in case they want to provide negative feedback.

External threats. We targeted MDE experts as our survey participants to make sure they can provide us relevant and high-quality feedback. However, this may also be a threat to the survey's results since some of the participants may be biased about how, e.g., the problem of executing partial models should be dealt with.

7 RELATED WORK

A large amount of related work exists, and only the most relevant can be discussed here. Existing work can be divided into three categories: (1) work on model-level debugging and execution, (2) work on partial models, which tries to address specification, analysis, and transformation of partial models, and (3) work on partial programs that deals with the parsing, analysis, and completion of partial programs in the context of different programming languages.

Model-level execution and debugging. Existing techniques of model execution are based on either interpretation or translation. Interested readers can refer to [14] which provides a comprehensive survey of existing work in the context of the model execution.

Model-level debugging techniques can be classified into interactive debugging and debugging by tracing. Interactive debugging allows users to directly investigate and modify the execution of models during the execution, by providing features such as setting breakpoints and stepping over the execution. Interactive model-level debugging is supported by several MDD tools, e.g., Matlab StateFlow [57], AF3 [12], xtUML [58] and YAKINDU [11]. We also presented a new approach for supporting interactive model-level debugging in [13], [33] by using model transformation techniques.

In debugging by tracing, the model or the generated code is instrumented to generate useful execution traces. Then, the traces are collected and used for offline analysis and debugging. Hojaji et al. [59] surveys the existing work in the context of model execution tracing. Examples of existing work and MDD tools supporting trace analyses via code instrumentation include [60], [61], [62], [63], [64], [65]. For instance, Iyengar et al. [63], [64], [66] propose an optimized model-based debugging technique for RTE systems with limited memory. They use a monitor on the target platform to collect the generated traces and a debugger (executed on a host with sufficient memory) to analyze the traces offline, and to display results on the model elements. Das et al. [67] propose a configurable tracing tool based on LTtng. They rely on code instrumentation to produce tracepoints useful for LTtng.

To the best of our knowledge, none of the existing work in the context of model execution and debugging supports the execution and debugging of partial models.

7.1 Partial models

In the context of MDD, the partial models are mainly used to deal with uncertainties of type ‘known unknown’. Existing research proposes mechanisms to define partial models using relaxed meta-models [68], model annotation [69], UML profiles [70], and graphical notations [71]. They leverage the partial models for analysis [69], [72], requirement management and analysis [73], testing [68], [74], and bi-directional transformation [75]. Also, some research addresses the refinement [76], [77], transformation [78] and completion [79] of partial models. E.g., the wok [69], [80] presents a rich formalism for partial models, which marks model elements with four special annotations (may, set, variable, and open) with well defined semantics. They show how the partial models can be concretized into possible design candidates. Sen et al. [68] present a semi-automated tool that supports the specification and completion of partial models, which are used for the testing of model transformations. They show that the testing of model transformations using partial models is as effective as using human-made models.

To the best of our knowledge, no work in the context of partial models addresses the execution and debugging of partial models. Our work does not require specification of partial elements explicitly by users, since it detects all of them automatically by static analysis. Automatic detection of partial elements allows users to execute the models with minimum effort. Note that the partiality that our approach detects only concerns the execution, and may not be suitable for managing uncertainties in requirements or design models.

7.2 Partial programs

An extensive body of work exists for dealing with and leveraging partial programs. The most important of them can be classified as follows.

(1) Parsing of partial programs Typically existing compilers can handle only complete programs. As a partial program is a subset of a complete program, many of its variables' types and library calls are unknown. Thus, parsing partial programs requires extra effort, mainly for the inference of missing types, and resolving unknown function calls. E.g., Zhong et al. [81] propose an approach that resolves unknown types and function calls for partial Java programs by analyzing the existing complete program versions. Melo et al. [82] present a technique to support the compilation of incomplete C code.

Koppler [83] presents a systematic approach to implement fuzzy parsers, which extract high-level structures out of incomplete or syntactically incorrect programs. Moonen [84] proposes a solution in the form of island grammars that partitions code into islands (recognizable constructs of interest) and water (remaining parts). Dagenais et al. [85] propose a framework that uses heuristics to recover the declared type of expressions and resolve ambiguities in partial Java programs. Note that since the models are saved in the form of an abstract syntax tree (AST), the need for this type of research is unnecessary in the context of MDD.

(2) Partial program analysis/verification to deal with poor scalability and missing components E.g., modular model checking, introduced in [86], verifies properties of system modules, under some assumptions about the environment. Colby et al. [87] present an approach for automatically closing an open concurrent reactive system (i.e., a system
with missing components) by generating an environment that can provide any input at any time to the system. This result is a self-executable system, which can exhibit all the possible reactive behaviors of the original system and therefore can be used for the state space exploration that is required for verification and analysis purposes. Our refinement of absent/ignored components is similar to this work.

(3) Program synthesis techniques based on partial programs (synthesis by sketching). Instead of synthesizing a program from scratch, work in this category uses a partial program (i.e., a program with holes) along with a specification, test harness, or reference implementation, and tries to fill the holes using synthesis techniques. E.g., Solar-Lezama et al. [88] introduce the concept of programming with sketches and presents Stream Bit as a new programming approach based on sketching. Existing sketching techniques (e.g., [89]) translate the partial program into a propositional satisfiability problem, and leverage counter-example-guided inductive synthesis to generate a program using existing SAT solvers. Hua et al. [90] introduce EdSketch that performs execution-driven sketching for synthesizing Java programs using a backtracking depth-first search.

8 Conclusion and Future Work

In this paper, we have proposed a conceptual framework for the execution and debugging of partial models, which consists of static analysis, automatic refinement, and input-driven execution. Using static analysis, we extract the problematic elements that prevent execution. The problematic elements are automatically fixed by adding decision points and related specifications into the partial models. Finally, the refined models are executed with the help of user input, either interactively or via a script. We have created a debugger for the debugging of partial UML-RT models (PMExec) based on the proposed framework. We have applied PMExec to the debugging of several use-cases, and have evaluated its performance for analysis, refinement, and handling of users input. Despite being a prototype, the performance of PMExec is acceptable, which shows that our approach is a viable approach for the debugging of partial models.

We have made the implementation of PMExec publicly available. The modeling community can extend it and use it for more research on, e.g., (1) the exhaustive execution of partial models for testing or run-time verification, (2) the synthesis of models by sketching, (3) using the proposed framework to support partial execution and debugging of partial models expressed in other modeling languages, and (4) automatic completion of missing specifications, rather than taking inputs from users.

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